Homogeneous Hydrogenations and Related Reductive Reactions Catalyzed by Rhenium Complexes

DISSERTATION

zur

Erlangung der naturwissenschaftlichen Doktorwürde

(Dr. sc. nat.)

vorgelegt der

Mathematisch-naturwissenschaftlichen Fakultät

der

Universität Zürich

von

Rajesh Kunjanpillai

aus

Indien

Promotionskomitee

Prof. Dr. Heinz Berke (Vorsitz und Leitung)

Prof. Dr. Roger Alberto

Zürich 2013

Homogeneous Hydrogenations and Related Reductive Reactions Catalyzed by Rhenium Complexes

DISSERTATION

zur

Erlangung der naturwissenschaftlichen Doktorwürde

(Dr. sc. nat.)

vorgelegt der

Mathematisch-naturwissenschaftlichen Fakultät

der

Universität Zürich

von

Rajesh Kunjanpillai

aus

Indien

Promotionskomitee

Prof. Dr. Heinz Berke (Vorsitz und Leitung)

Prof. Dr. Roger Alberto

Zürich 2013

Dedicated to my father

N. Kunjan Pillai

(1935-1993)

List of Abbreviations

Acronym	**Full Name**
TOF	Turn Over Frequency
TON	Turn Over Number
THF	Tetrahydrofuran
TMP	2,2,6,6-Tetramethylpiperidine
DMF	N,N-Dimethylformamide
p-TsOH	*p*-Toluenesulfonic acid
equiv.	equivalents
KIE	Kinetic Isotopic Effect
Me	methyl
Et	ethyl
Pr	propyl
Bu	butyl
Ph	phenyl
o	*ortho*
m	*meta*
p	*para*
n	*normal*
i	*iso*
t	*tertiary*
cy	*cyclo*

h	hour
IR	Infrared
ν	frequency
vs	versus
NMR	Nuclear Magnetic Spectroscopy
δ	chemical shift
ppm	parts per million
Hz	Hertz
s	singlet
d	doublet
t	triplet
q	quartet
quin	quintet
GC/MS	Gas Chromatography/Mass Spectroscopy
min	minute
ΔG^o	standard Gibbs free energy change
ΔH^o	standard enthalpy change
ΔS^o	standard entropy change
kJ	kilo Joules
K	Kelvin
°C	degree Celsius
g	gaseous
aq	aqueous
eq	equation

Table of Contents

1. General Introduction

1.1. Significance of Catalysis

Efficient and environmentally friendly transformations are challenging goals in chemical synthesis. The greatest achievements in these respects have evoked from the concept of 'catalysis'. A catalyst is any substance that increases the rate of a reaction without itself being consumed; and the process of application of it can be termed as catalysis. About 90% of all commercially produced chemical products involve catalysts at some stage in the process of their manufacture.[1] It is extensively applied in energy processing, production of bulk, fine and intermediate chemicals etc. The two broad classification of catalysis are homogeneous and heterogeneous catalysis. In the homogeneous catalysis, the catalyst and the reactants are in the same phase where as in heterogeneous catalysis, the catalyst is in a different phase, mostly solid, than the reactants. In contrast to heterogeneous catalysis, homogeneous catalysis paves the way for deep understanding of their mechanisms and thus provides the opportunity for rational turning of the catalyst. Thus homogeneous or molecular catalysts offer improved selectivity, increased activity, and allow operationally lower temperatures.

1.2. Hydrogen and its Activation

Hydrogen molecule (H_2) is the lightest element and is an abundant clean resource. The hydrogen atoms in H_2 molecule is strongly held together by covalent bond and has dissociation energy of 104 kcal/mole. One of the common methods to activate this high strength non-polarized bond is by using transition-metal centres bearing suitable ligands. The

hydrogen molecule can coordinate to a metal centre in a side-on fashion (η^2) primarily *via* donation of its two σ electrons to a vacant d orbital of the metal to form a stable dihydrogen complex. The first structurally characterized dihydrogen metal complex $W(CO)_3(P\textit{i}\text{-}Pr_3)_2(H_2)$ was discovered in 1983 by Kubas and co-workers.[2] The stabilization of η^2-H_2 complexes arises from the back donation of electrons from a filled metal d orbital of metal to the σ* anti bonding orbital of H_2. The back donation is analogous to that of Dewar-Chatt-Duncanson model for olefin coordination (Figure. 1.1).[3]

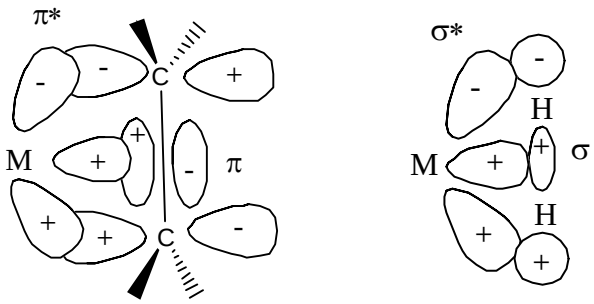


Figure 1.1. Dewar-Chatt-Duncanson model for olefin coordination (left) and bonding model for H_2 coordination (right).

There are two modes of its activation; homolytic (considered as two H radicals) and heterolytic splitting of dihydrogen (considered as a H^- and a H^+).

The homolytic splitting of dihydrogen leads to the oxidation of the metal leading to the formation of metal dihydrides and thus oxidative addition of dihydrogen takes place. A pictorial representation along with the H-H distance is depicted in Figure 1.2.

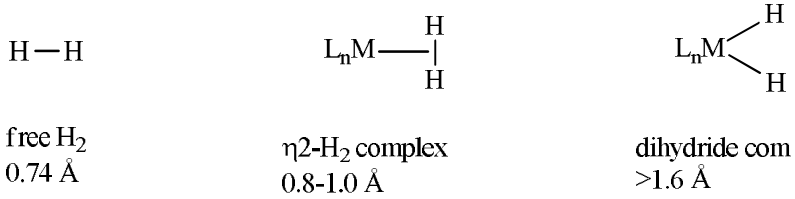
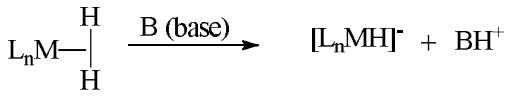


Figure. 1.2. Oxidative addition of H_2 and H-H distances.

Metal dihydrogen complexes have higher thermodynamic and kinetic acidity compared to most metal hydride complexes.[2b,4] H_2 is a very weak acid (pKa = 35 in THF), but η^2-binding with a metal centre increases the acidity up to 40 times. The pKa of η^2-H_2 can be as low as -6 and thus becoming acidic as strong as sulfuric acid or triflic acid.[5] Therefore



Scheme 1.1. Heterolytic Splitting of H_2.

the presence of a base can lead to the deprotonation from metal dihydrogen complex leading to "heterolytic" splitting of dihydrogen as depicted in Scheme 1.1.

1.3. Homogeneous Hydrogenation

Hydrogenation is one of the most extensively studied reactions in homogeneous catalysis.[6] Homogeneous hydrogenation is often carried out with molecular hydrogen although much attention has been paid to derive hydrogen from other molecules which are capable of donating hydrogen, like alcohols, formic acid salts etc. The latter processes are termed as transfer hydrogenations.[6] Transition metals are capable of exhibiting variable oxidation states which could be stabilized by a large variety of ligands. The ligands often appear are negative donors like hydrides, halides, alkyls or neutral donors like amines, imines, nitriles, phosphines, carbon monoxide, η^2-alkenes, η^5-C_5H_5 or positive donors like nitrosyl etc. In this context, highly efficient and selective catalysts are available for the hydrogenation of unsaturated substrates including their asymmetric versions. Hydrogenation or related reduction reactions are often carried out with suitable orgaonsilanes which are termed as hydrosilylations. The developments in the area of organometallic chemistry paved the way for the preparation of a variety of metal complexes, particularly those of transition metals, active for hydrogenation and transfer hydrogenation as well as hydrosilylation reactions under mild conditions.

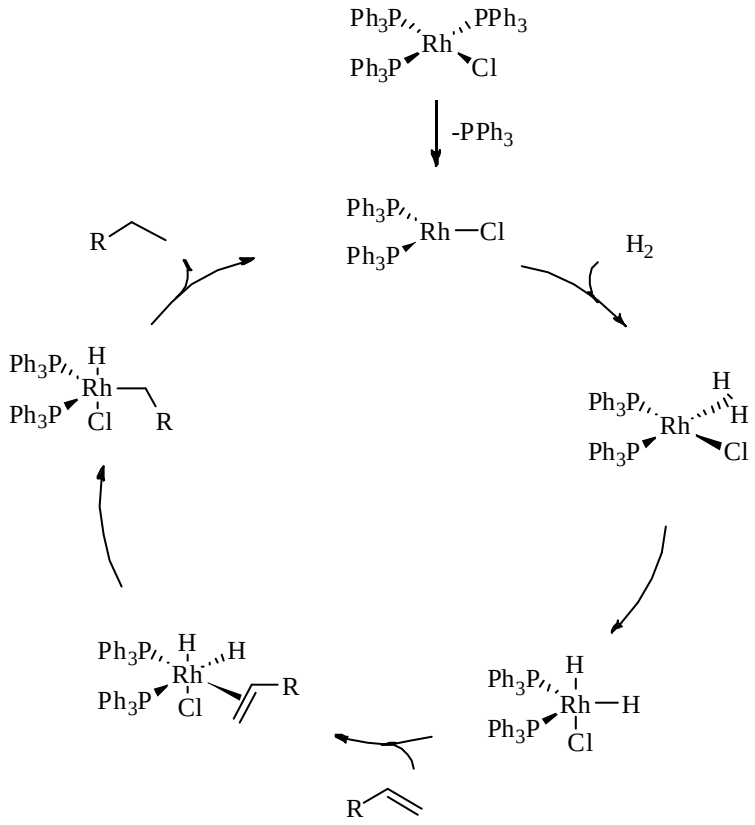
1.4. Hydrogenation of Various Functional Groups

1.4.1. Hydrogenation of Alkenes

The first documented example of homogeneous hydrogenation by metal compounds was reported by Calvin in 1938, reporting that quinoline solutions of copper acetate, at 100 °C, were found to be active catalysts for the hydrogenation of quinines[7]. The most significant advances in homogeneous hydrogenation catalysis have been the discovery of rhodium phosphine complex $[RhH(CO)(PPh_3)_3]$ by Bath and Vaska in 1963.[8] Later in few years, the catalytic activity of this complex for hydrogenation, isomerisation and hydroformylation reactions were reported by Wilkinson and co-workers.[9] The most important rhodium catalyst, the $[RhCl(PPh_3)_3]$ complex, was reported during the period 1965-1966 independently by Wilkinson, Bennett and Vaska.[10] Wilkinson and co-workers extensively studied the remarkable catalytic properties of this complex, which is usually known as Wilkinson's catalyst. This turned out to be the first practical hydrogenation system working usually at room temperature and atmospheric pressure of hydrogen. During this time $[IrCl(CO)(PPh_3)_2]$ was discovered by Vaska, called Vaska's complex,[11] which was susceptible for oxidative addition-reductive elimination with dihydrogen to form $[IrH_2Cl(CO)(PPh_3)_2]$ whose activity was very weak. Also, the iridium analogue of Wilkinson catalyst, $[IrCl(PPh_3)_3]$ was also weakly active.[10b] The almost inactivity of these complexes towards hydrogenation were due to inability to form vacant sites by dissociation of PPh_3 ligand from $[IrH_2(PPh_3)_3]$. For the two decades, rhodium chemistry dominated in the field of hydrogenation, due to the remarkable investigations of Wilkinson, Kagan, Osborn, and Knowles.[12] Ruthenium was slowly developing during these period starting with studies by Halpern[6,13] and Wilkinson.[6,14] In 1965, Wilkinson and co-workers found that the reaction of $RuCl_2(PPh_3)_3$ with hydrogen and a base gave the hydride complex $RuHCl(PPh_3)_3$, a very active catalyst for hydrogenation.[13] This monohydride complex is formed by the abstraction of proton from the

acidic η^2-dihydrogen ruthenium complex by the base. This interpretation was arisen after the isolation of metal dihydrogen complexes by Kubas.[2a] However, this ruthenium system operates at 0.66 bar of H_2 pressure at 25 °C showing TOF of 10^4 in the hydrogenation of 1-octene. It is almost 20 times active when compared to the well-known Wilkinson's catalyst $RhCl(PPh_3)_3$ under similar conditions.[15]

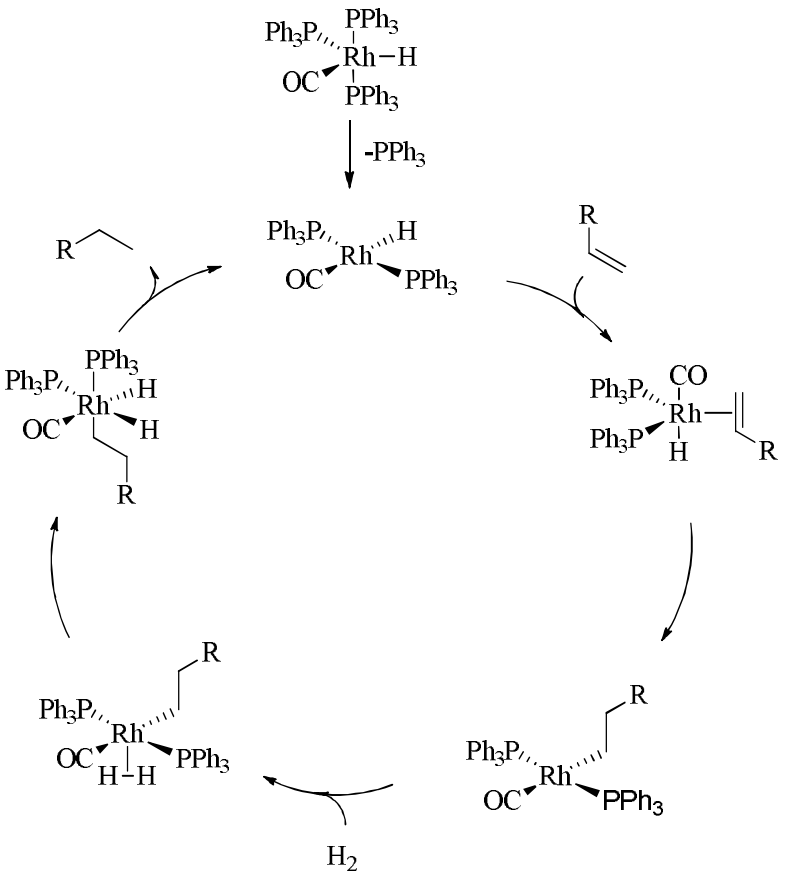
Halpern came up with a more promising mechanism for alkene hydrogenation[16], and is supported by careful kinetic and spectroscopic studies of hydrogenation of cyclohexene. The predominant hydride route consists of oxidative addition of a hydrogen molecule prior to alkene coordination (H_2 before olefin; known as Wilkinson-type hydrogenation). The complex $[RhCl(PPh_3)_3]$ undergoes dissociation of PPh_3 to form the 14-electron species $RhCl(PPh_3)_2$ (Scheme 1.2). The rapid oxidative addition of hydrogen to $RhCl(PPh_3)_2$,



Scheme 1.2: Wilkinson-type (H_2 before olefin) mechanism of hydrogenation of olefins by $RhCl(PPh_3)_3$.

followed by alkene coordination, affords the 18-electron octahedral dihydride alkene complex $[RhH_2Cl(alkene)(PPh_3)_2]$. The rate-determining step for the whole process is the intramolecular alkene insertion into the rhodium-hydride bond of $[RhH_2Cl(alkene)(PPh_3)_2]$, to produce the alkyl hydride intermediate, $[RhH(alkyl)Cl(PPh_3)_2]$. The next step, the reductive elimination of alkane from this alkyl hydride intermediate to regenerate occurs rapidly. The proposed cycle implies changes in the oxidation state (I and III) in the oxidative addition and reductive elimination.

In the case of saturated 18-electron complex $[RhH(CO)(PPh_3)_3]$, dissociation of PPh_3 and creation of a vacant coordination site gives rise to the catalytic active species, $[RhH(CO)(PPh_3)_2]$[17] (Scheme 1.3). Coordination of the alkene substrate to $[RhH(CO)(PPh_3)_2]$ (Olefin before H_2; known as Osborn-type hydrogenation) followed by the

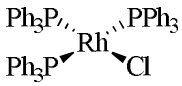
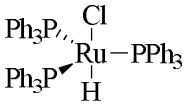
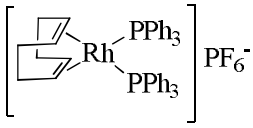
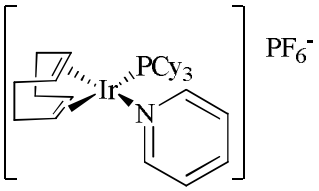
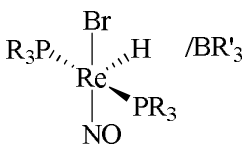


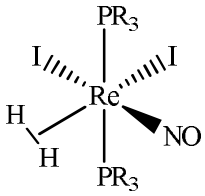
Scheme 1.3: Osborn-type (olefin before H_2) mechanism of hydrogenation of olefins by $RhH(CO)(PPh_3)_2$.

insertion of the hydride to the coordinated alkene takes place to form the Rh(alkyl) species. Oxidative addition of H_2 followed by reductive elimination would regenerate the active species $RhH(CO)(PPh_3)_2$.

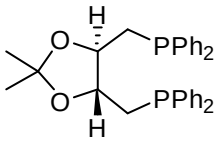
A large variety of homogeneous catalytic systems that efficiently hydrogenate a variety of olefins has been reported. Among them, the most active systems effective for 1-hexene hydrogenations are depicted in Table 1.2.

Table 1.2. Catalytic activity of several well-known Wilkinson and Osborn type catalysts in 1-hexene hydrogenation.[18]

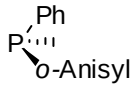
Entry	Catalyst	Solvent	Temp (°C)	H_2 (bar)	TOF (h^{-1})
1[10b]	 Wilkinson catalyst	C_6H_6/EtOH	25	1	650
2[15]		C_6H_6	25	1	9000
3[19,20]	 Schrock-Osborn catalyst	CH_2Cl_2	25	1	4000
4[20]	 Crabtree catalyst	CH_2Cl_2	0	1	6400
5[18a]	 Berke catalyst	Solvent free Solvent free CH_2Cl_2	23 23 90	1 10 10	1725 17000 56000

6[18b]		/BR'_3/R_3SiH Berke catalyst	Solvent free	23	10	6.0×10^5

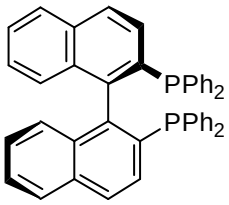
The most significant step further was the use of chiral phosphines with Rh precursors, realizing catalytic enantioselective hydrogenation reported in 1968 by the groups of Knowles[21] and Horner.[22]



(-)-DIOP



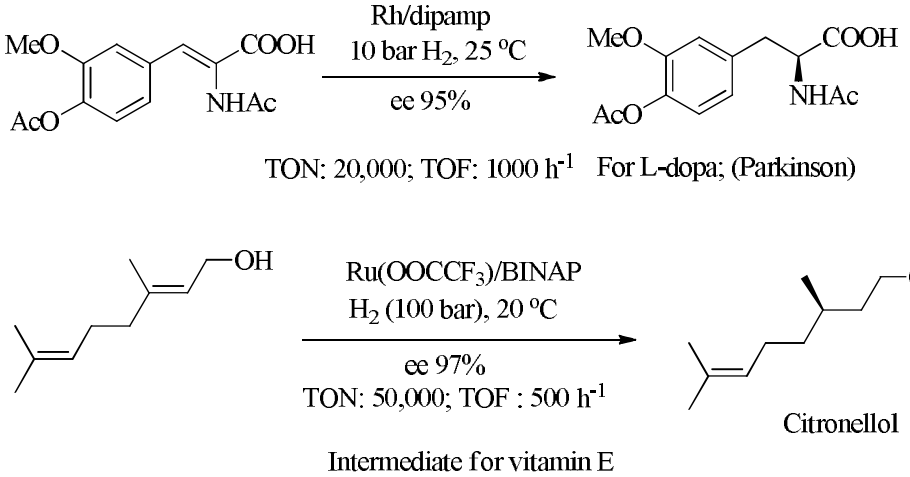
PAMP



(*R*)-BINAP

Figure 1.3. Chiral ligands with different modes of origin of chirality used in asymmetric hydrogenation reactions.

A large number of subsequent publications have reported the development of catalytic systems containing a variety of chiral ligands for hydrogenation of a wide range of prochiral substrates including alkenes, ketones and ketimines. Processes reaching enantiomeric excess



Scheme 1.4. Examples of asymmetric hydrogenation of C=C bonds operating in industry.

(ee) close to 100% are now a days common. Also, at least in few cases, their mechanisms could be understood in detail. More than a dozen of industrial, catalytic enantioselective homogeneous hydrogenation processes are now operating in fine and intermediate chemical industries particularly for pharmaceuticals and agrochemicals. Few of such systems involving C=C bond hydrogenation are given in Scheme 1.4.[23]

1.4.2. Hydrogenation of Aldehydes and Ketones

The reduction of carbonyl compounds to their corresponding alcohols is one of the most fundamental and widely employed reactions in synthetic organic chemistry. Though aluminium and boron hydride reagents are often used in laboratory for their reductions, in an industrial and practical point of view, procedures that make use of molecular hydrogen show better ecology, are more cost-effective, and are potentially easier to operate than those require the clean-up of boron or aluminium waste at the end of the reaction.

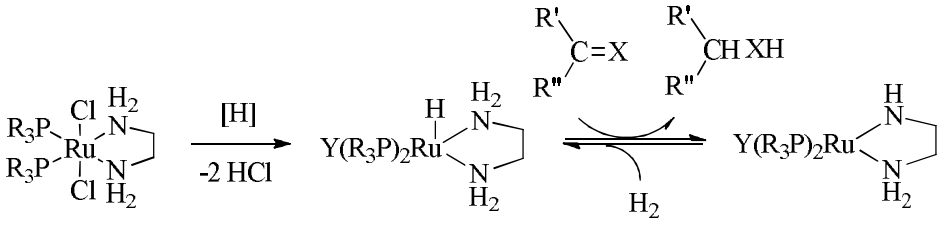
1.4.2.1. Aldehydes

The first report of a catalytic system for the effective homogeneous hydrogenation of an aldehyde to an alcohol was reported in 1967.[24] Coffey reported that the use of a catalyst prepared *in situ* by the reaction of $[Ir(H)_3(PPh_3)_3]$ with acetic acid was effective for the hydrogenation of *n*-butyraldehyde to *n*-butanol at 50 °C and under 1 bar of H_2 pressure. This catalytic system was further studied by Strohmeier and Steigerwald, who performed reactions at 10 bar without solvent to achieve hydrogenation of a series of aldehydes.[25] Turnover numbers (TON) of up to 8000 were achieved in the case of the hydrogenation of benzaldehyde. Wilkinson catalyst $[RhCl(PPh_3)_3]$, a convenient catalyst for the hydrogenation of olefins, was found to be deactivated by aldehydes to give the catalytically inactive complex $[RhCl(CO)(PPh_3)_2]$ as a result of the competing decarbonylation reaction.[10b] Strohmeier and Weigelt used the catalyst $[RuCl_2(CO)_2(PPh_3)_2]$ to hydrogenate a series of

aldehydes at 15 bar H_2 and at 160-180 °C, with generally high yield and turnover numbers;[26] TONs of upto 56000 were achieved in the hydrogenation of benzaldehyde and that of 59400 were achieved in the hydrogenation of 2-methylpentanal. Although these are amongst the highest turnover numbers reported for aldehyde hydrogenation, the reactions were carried out at relatively high temperatures. $[RuHCl(CO)(PPh_3)_3]$ when used in the hydrogenation of propionaldehyde with a SCR of 50 000, TONs of up to 32000 were achieved after 50 h at 140 °C under 30 bar H_2.[27] Using this same catalyst in the reduction of crotonaldehyde, the favoured product was the fully saturated alcohol.[28]

1.4.2.2. Ketones

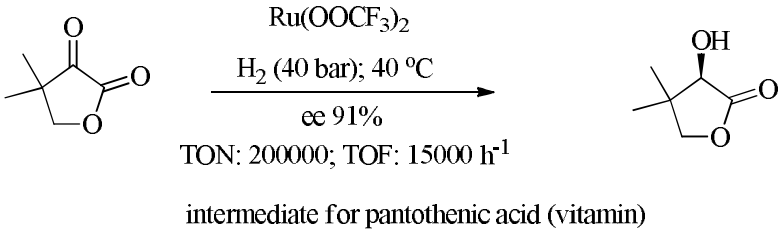
$[Rh(bpy)_2]^+$, obtained by the *in situ* reduction of [Rh(bpy)2Cl2]Cl with hydrogen in methanolic sodium hydroxide,[29] can reduce a series of simple ketones under 1 bar H_2 and at 30 °C.[30] One of the notable catalytic system $Ru(Cl)_2$((*S*)-tolbinap)((*S*,*S*)-dpen)/t-BuOK syatem designed by Noyori and co-workers could hydrogenate acetophenone in TON of 2.4 x 10^6 with TOF of 2x 10^5 under a H_2 pressure of 45 bar at 30 °C, providing 80% ee in 2-propanol as solvent.[31] The complex $[RuCl_2(PPh3)_3]$ was also active for the hydrogenation of ketones and Noyori and coworkers in 1995 found out that the activity of this complex could be enhanced by the addition of ethylenediamine (en) and KOH/*i*-PrOH.[32] Using this system, with a catalyst loading of 0.02 mol%, Ru: en: KOH, 1 :1 : 20, at 28 °C under 3 bar H_2, TOFs of 6700 h^{-1} were realized in the hydrogenation of acetophenone. By increasing the pressure to 50 bar and using a SCR of 10 000, TOFs in excess of 23 000 were obtained. This system was even shown to work at -20 °C, indicating the mildness of the conditions. The screening of various amines revealed that at least one primary or secondary amine end was necessary along with a base to improve activities. Subsequently Noyori and coworkers isolated the stable precatalysts amino phosphine complexes *trans*-$[RuCl_2(phosphane)_2(1,2\text{-diamine})]$



Scheme 1.5. Noyori's metal-ligand bifunctional catalysis for hydrogenation of ketones applying a $RuCl_2(PR_3)_2$(diamine)/base system in 2-propanol. (X = H, or alkoxy/amino).

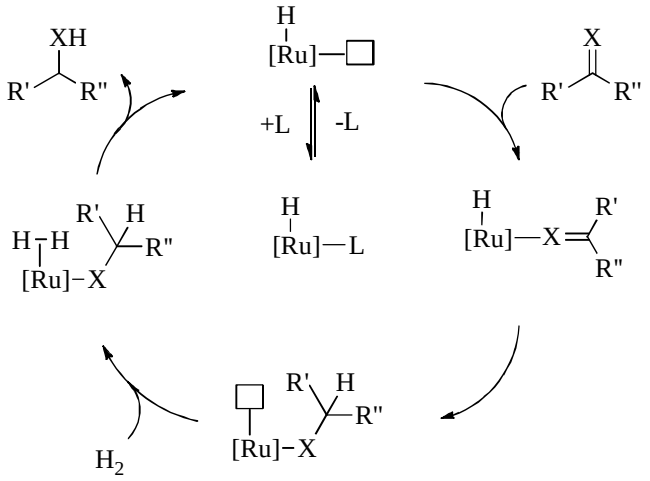
which showed more rapid hydrogenation of ketones than the in situ systems.[33] These findings paved a break-through in the field with the concept of 'metal-ligand bifunctional catalysis' with outer sphere coordination mechanism (Scheme 1.5).

The years after witnessed the application of this concept emerging a large number of documentations particularly in the area of enantioselective hydrogenations and transfer hydrogenations of ketones and ketimies. One of the enantioselective ketone hydrogenations operating in industry is shown in Scheme 1.6.[23a,e]



Scheme 1.6. Example of asymmetric hydrogenation of C=O operating in industry.

However, the classical mechanism would operate in metal complexes bearing at least a hydride ligand and a vacant site *cis* to each other. Linn and Halpern proposed a mechanism involving such a type of species.[34] They found that H_2 dissociates from $RuH_4(PPh_3)_3$ (later found as $(Ru(\eta^2\text{-}H_2)H_2(PPh_3)_3)$ when the ketone coordinates. Coordination of the ketone to the ruthenium hydride species followed by the insertion of it into the Ru-H bond would generate an alkoxide intermediate $RuH(OR)(PPh_3)_3$ (Scheme 1.7). Hydrogen coordination



Scheme 1.7: Classical mechanism of hydrogenation of aldehydes, ketones and imines. [Ru]=$RuH(PPh_3)_3$, L=H_2; X = O, NR).

followed by the rapid elimination of alcohol would regenerate the ruthenium hydride species. The same mechanism is operative also for aldehydes and imines.

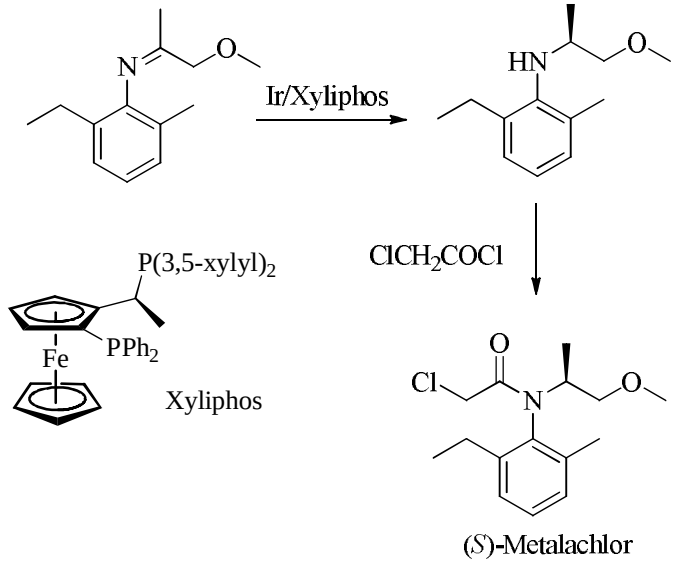
1.4.3. Reductive Amination and Imine Hydrogenation

Aldehydes or ketones react with amines to form carbinolamines or imines which are subsequently reduced to substituted amines are called reductive amination with respect to carbonyl compound or reductive alkylation with respect to the amine. This reaction using sodium borohydride or sodium cyanoborohydride is well established. However, a more environmentally benign, economical and practical method to carry out this reaction is to use molecular hydrogen. Though several heterogeneous catalysts have been shown to be effective in this transformation, the main focus is to use more controllable homogeneous catalysts. The first example of this type of transformation was reported by Mark′o and Bakos in 1974 using Co and Rh carbonyls[35]. In 2000, Borner and coworkers described a more practical catalytic system for these reactions.[36] Reductive alkylation of piperidine with benzaldehyde could be achieved using [Rh(dppb)(COD)]BF_4 or [Rh(1,2-bis-diphenylphosphinitoethane)(COD)]BF_4 under mild conditions 50 bar H_2 at room temperature with moderate selectivity towards the

desired tertiary amine with the formation of the corresponding alcohol. Beller and co-workers reported a more practical system for reductive amination of aromatic aldehydes using ammonia.[37] $[Rh(cod)Cl]_2$ along with TPPS ligand and NH_4OAc furnished 86% of benzylamine with a TOF of 1720 h^{-1}under 50 bar H_2 at 135 °C.

The reaction of $RuCl_2(PPh_3)_3$ with diphosphines with medium bite angles (dppb, diop, binap) produces complexes $RuCl_2$(diphosphine)(PPh_3) that are used as catalysts for the hydrogenation of imines.[38] The dppb complex can be converted to the binuclear dihydrogen complex (η^2-H_2)(dppb)Ru(μ-Cl)$_3$Ru(dppb)Cl, which is a precatalyst for the hydrogenation of aldimines.[39] The PPh_3 ligands in $RuHCl(PPh_3)_3$ can be displaced with P-N ligands produce a range of analogous precatalysts such as RuHCl(diamine)$(PPh_3)_2$ and *trans*-RuHCl(diamine)(diphosphine). When the former diamine compound is activated with alkoxide base under H_2, it is an active catalyst for ketone and imine hydrogenation,[40] while the latter is a precatalyst for the asymmetric hydrogenation of imines and ketones under mild conditions [41] both operating through 'metal-ligand bifunctional catalysis.

At this point, it worth mentioning the synthesis of the herbicide *S*-Metalachlor by the



Scheme 1.8. Synthesis of *S*-Metalachlor by the asymmetric hydrogenation of a C=N bond.

enantioselective hydrogenation of an imine using an $[Ir(COD)Cl]_2$/Xyliphos system developed by Blaser and co-workers, resulting in an extremely high TON = 2×10^6, TOF = 4×10^5 h^{-1} (Scheme 1.8).[42] However, the enantioselectivity does not exceed 80%. For an agrochemical, this enantioselectivity proved to be sufficient. This process is used industrially, presently run on a scale of 10,000 ton/year and is the largest asymmetric catalytic process today. It is the first example of asymmetric imine hydrogenation that was successfully applied in industry.

1.4.4. Hydrogenation of Nitriles

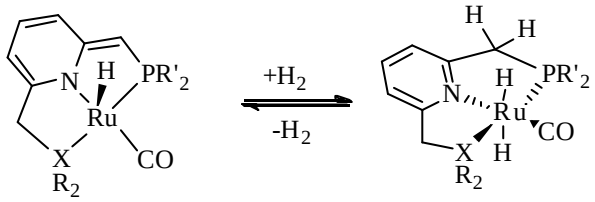
Nitriles are one of the most difficult classes of substrates to hydrogenate.[43] When they are subjected to hydrogenation, concomitant with the reduction processes, crucial selectivity probles arises: the formation of mixtures of primary, secondary and tertiary amine, as well as intermediate imines.[44] Homogeneous hydrogenation of nitriles to primary amines were reported by Beller and co-workers applying *in situ* $Ru(COD)(methylallyl)_2$/DPPF catalytic system at 50 bat H_2 at temperatures of 80-140 °C.[45] At 140 °C, TOF of up to 4800 h-1 were realized with yields close to 100%. A notable example of hydrogenation of nitriles to primary amines was documented by Sabo-Etienne and co-workers using $Ru(\eta^2\text{-}H_2)_2H_2(PCy_3)_2$. Under mild conditions of 3 bar of H_2 at 22 °C, 0.5 mol% of the catalyst provided 98% yield of the primary amine in 2 h (TOF: 98 h^{-1}).[46] Quite recently, Milstein and co-workers reported a Ru(PNN) system operating at 4 bar H_2 pressure at 70 °C furnishing secondary imines with good selectivities.[47]

1.4.5. Hydrogenation of Carboxylic esters

The hydrogenation of acids and esters using molecular hydrogen is generally a difficult task. Lithium aluminum hydride and certain boron hydrides are traditionally used for this reduction. However, the use of a stoichiometric aluminium reagent is not atom-economical

and requires the separation and disposal of large quantity of waste. As an ideal and green alternative to any of the stoichiometric procedures, catalytic hydrogenation using molecular hydrogen is a versatile tool and would attract industrial attention if a catalyst were sufficiently active. Heterogeneous catalysts capable of carrying out this process operate under very harsh conditions which limits their application. Grey et al reported the first homogeneous hydrogenation of an ester to alcohol.[48] The complex $K_2[Ru_2(PPh_3)_3(PPh_2)H_4]_2$.diglyme could hydrogenate methyltrifluoroacetate to trifluoroethanol and methanol at 90 °C under 6 bar H_2. However, formate esters were found to decompose with the liberation of carbon monoxide under these reaction conditions.

Milstein and co-workers reported the hydrogenation of methyl formate, dimethyl carbonate and carbamates using a Ru(PNN)(CO) system. Methyl formate could be obtained in TON of 4700 with 97% yield when a pressure of 50 bar at 110 °C was adopted.[49] The mechanism proceeds through H_2 splitting resulting in the formation of Ru-H and a C-H where it is driven by the aromaticity of an attached tridentate pyridyl ligand. This is popularly known as Milstein's aromatization-dearomatization principle (Scheme 1.9).



X = N, P; R = *i*-Pr, *t*-Bu

Scheme 1.9. Activation of H-H bond by Milstein's PNN and PNP based Ru system.

Ester hydrogenation catalyzed by a ruthenium(II) complex bearing an *N*-heterocyclic carbene tethered with an NH_2 operating through metal-ligand bifunctional catalysis has been

reported by Morris et al recently.[50] TOFs of up to 1500 h^{-1} were accomplished at a H_2 pressure of 25 bar at 50 °C in the hydrogenation of phthalide.

1.4.6. Hydrogenation of Carbon Dioxide and Carbonates/Bicarbonates

The inexpensive, abundant, low toxic CO_2 gas is one of the major reasons for green house effect and thereby leading to global warming and climatic changes.[51] The burning of fossil fuels to serve the energy demands of the world has been led a greater extend to the accumulation of this gas.[52] The future energy demand rely on long lasting or renewable methods since it is estimated that the fossil fuel sources will deplete in the near future.[53] In these contexts, production of synthetic fuel from climate threatening sources would be a method of choice and as a step; the hydrogenation of carbon dioxide to methanol, a C_1 feed stock, is highly demanding to run the daily needs of the future, there by tackling the issue of global CO_2 emissions.[54]

Hydrogenation of CO_2 to methanol has been reported with heterogeneous catalytic systems. Most prominent among them are the Cu-Zn based systems that operate at high temperatures and pressures.[55] In recent past, tremendous efforts are being made in academia to develop catalytic systems that are capable of reducing CO_2 to formates using well defined Ru, Rh and Ir systems.[56] Notable catalyst among these is an Ir-PNP pincer ligand system, reported recently by Nozaki and coworkers, for which TON and TOFs up to 3.5×10^5 and 1.5×10^5 respectively, were achieved.[57] Reduction of CO_2 to methanol has been achieved using boranes, phosphaboranes and silanes, but apart from the issue of high cost, these reagents lead to the formation of large amount of waste.[58] Preliminary outcome of efforts on metal catalyzed homogeneous reduction of CO_2 to MeOH was reported recently by Huff and Sanford through ruthenium catalyzed cascade reaction involving formic acid and methyl formate as intermediates.[59] In this report, different ruthenium complexes reported to be

capable of catalyzing CO_2 to formate level, and formate esters to methanol were rationally sequenced along with an acid co-catalyst, the latter was added to enhance esterification, all carried out in a single reaction vessel to effect this transformation. Quite recently, Leitner and co-workers demonstrated this reaction using ruthenium-phosphine catalytic system, which was already found to be efficient for the hydrogenation of carboxylic acids and their derivatives to the corresponding alcohols.[60] They reported a maximum TON of 221 under CO_2 pressure of 20 bar and H_2 pressure of 60 bar at 140 °C using a RuP_3/acid system. The role of acid was to enhance the esterification of the intermediate formic acid.

Recent years witnessed an emergence in the hydrogenation of bicarbonates and carbonates to formate salts. Like CO_2, the reductions of bicarbonates are also of considerable interest, because CO_2 can be easily trapped from waste streams in basic solution. Beller and co-workers recently developed a reversible energy storage system in which bicarbonates and carbonates is hydrogenated to the corresponding formates and the latter releases hydrogen on demand to form again bicarbonate.[61] A [{$RuCl_2$(benzene)}$_2$] and dppm system at a H_2 pressure of 80 bar furnished sodium formate in TON of 1100 and TOFs of 550 h^{-1} at a temperatures of 70 °C. The H_2 release was carried out at 40 °C with the same catalyst furnishing it in TON of 2000 with initial TOF's up to 2900 h^{-1}. In 2012, the same group reported a tetradentate FeP_4 system capable of hydrogenating $NaHCO_3$ to $NaHCO_2$ with TON of 7500 and TOF of 750 h^{-1} under a H_2 pressure of 60 bar at 100 °C.[62]

1.5. Transfer Hydrogenation

The transfer hydrogenation particularly the asymmetric transfer hydrogenation of ketones and imines is a useful tool in organic synthesis. Like catalytic hydrogenation, catalytic transfer hydrogenation is also considered to be an environmentally friendly transformation, the latter even much safer and convenient to handle on any scale. The first homogeneous transfer

hydrogenation was reported in 1925 when Meerwein and Schmidt described the reduction of ketones and aldehydes using alcohols as reductants and aluminum alkoxides as the catalysts.[63] The major difference from previous studies was the hydrogen source; instead of molecular hydrogen, a small organic molecule was utilized to provide the hydrogen necessary to reduce the carbonyl compound. A decade later, Oppenauer recognized the possibility of reversing the reaction into an oxidation procedure.[64]

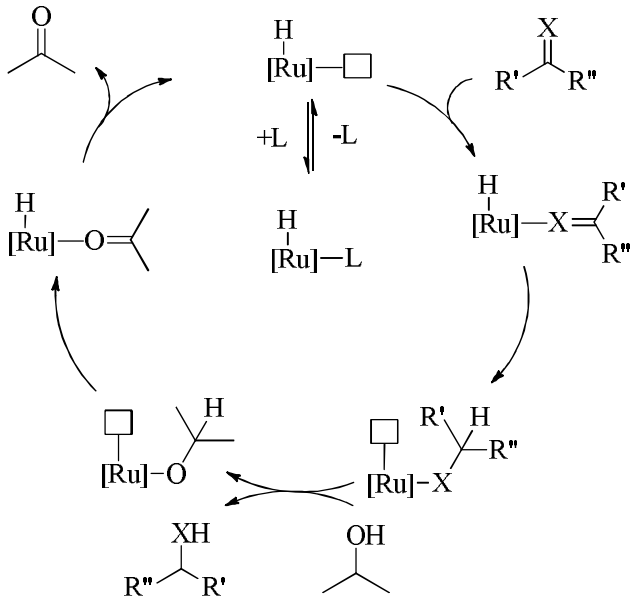
1.5.1. Transfer hydrogenation of Ketones and Imines

Although actually designed for hydrogenation with molecular hydrogen, Wilkinson catalyst ($RhCl(PPh_3)_3$) has also been used in transfer hydrogenation catalysis using 2-propanol as hydrogen donor.[10b] Today, several transition metal catalysts are available to perform the transfer hydrogenation of ketones and imines with acceptable efficiency particularly using 2-propanol as hydrogen donor. Though the classical primary coordination sphere mechanisms operating through the availability of a metal hydride and a vacant site are extensively reported on ruthenium monodentate phosphine systems[65] there has been a large number of literature on transition metal catalyzed transfer hydrogenation reactions designed to operate through Noyori[66] or Shvo[67] type secondary coordination sphere metal ligand bifunctional mechanisms with simultaneous proton and hydride transfers.

General mechanism for the classical type of transfer hydrogenations of ketones and imines is depicted in Scheme 1.10.[68]

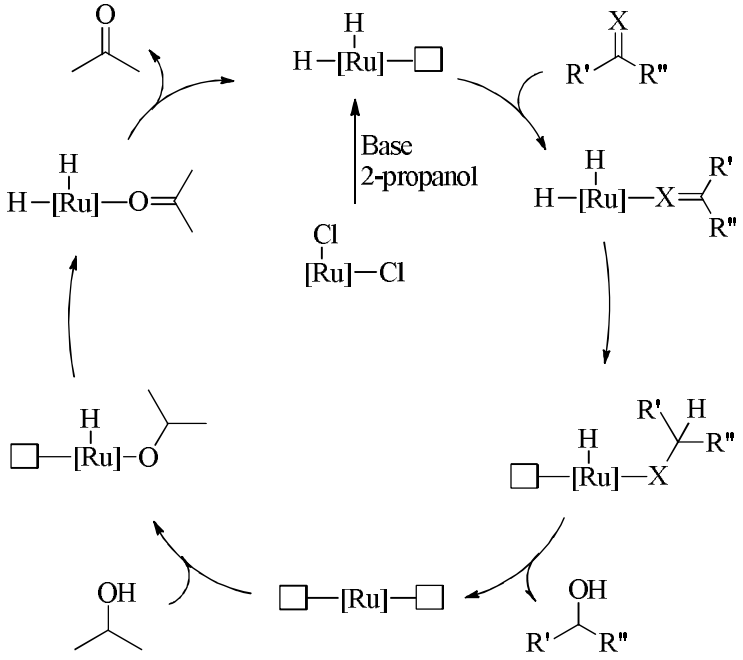
Pàmies and Bäckvall[65k,n] have proposed an alternative mechanism for transfer hydrogenations catalyzed by the dihydride $RuH_2(PPh_3)_3$ that is thought to be formed by the reaction of the precatalyst $RuCl_2(PPh_3)_3$ with base and 2-propanol (Scheme 1.11).

The key difference in these mechanisms is the generation of the reduced product, alcohol, through the protonation of the metal alkoxide species by 2-propanol or the reductive



Scheme 1.10. Conventional mechanism of transfer hydrogenation of aldehydes, ketones and imines.

elimination of the alcohol from the metal(alkoxide) hydride species the former does not change the oxidation change of the metal throughout the catalytic cycle where as the latter leading to an oxidation change of the metal.



Scheme 1.11. Mechanism of transfer hydrogenation of aldehydes, ketones and imines catalyzed by $RuCl_2(PPh_3)_3$.

Numerous reports on the transfer hydrogenation of ketones and imines operating through the classical inner coordination sphere transfer hydrogenation mechanism as well as outer coordination sphere metal ligand bifunctional mechanism are documented in literature.[6,69] The key interest in the recent research in this area of both ketone and imine transfer hydrogenation is in developing their highly efficient asymmetric versions.

1.5.2. Transfer Hydrogenation of Nitriles

Like catalytic hydrogen hydrogenation of nitriles, the catalytic transfer hydrogenation of nitriles is also a challenging aspect and only a very few number of literature is available in this area. The complex $RuH_2(PPh_3)_4$ catalyzes the transfer hydrogenation of benzonitrile to a mixture of the amines and imines; benzylamine (6%), the imine N-benzylidenebenzylamine (20%) and the secondary amine, dibenzylamine (25%) in 51% conversion when a loading of 1.25 mol% at 85 °C run for 80 h.[65e] Recently, Beller and co-workers developed a promising method for the transfer hydrogenation of various aromatic as well as secondary and tertiary nitriles in the presence of [{Ru(*p*cymene)Cl_2}$_2$]/DPPB /Base system in 2-butanol at 120 °C. TON of 280 h^{-1} could be achieved with moderate to good yields in most cases.[70] Quite recently, the same group reported the transfer hydrogenation of nitriles followed by subsequent N-monoalkylation to secondary amines.[71]

The $RuCl_2(PPh_3)_3$/NaOH/2-propanol(large excess) catalytic system at a temperature of 120 °C could furnish the N-isopropyl secondary amines in moderate to good yields.

1.6. Hydrosilylation of Nitriles

Transition metal catalyzed homogeneous hydrosilylations of aldehydes and ketones as well as imines are well established.[72] Unlike Si-H addition to C=X bond (X = C, O, NR), the CN triple bond remains a great synthetic challenge.[73] Hydrosilylation of nitriles also presents a difficult chemoselectivity problem in that the products of monoaddition, N-silylaldimines

R_3Si-N=CHR, are generally much more reactive than nitriles, so that the reaction proceeds further to give the disilylamines $(R'_3Si)_2NCH_2R$.[74] Since the report by Calas et al[75] on the $ZnCl_2$-catalyzed condensation of $HSiEt_3$ with PhCN to give the imine $PhHC=NSiEt_3$ in moderate yield of 54 at 140-150 °C, only a few catalytic monohydrosilylations of nitriles have been published.[74a,76] A notable one among them is the complex [Cp(*i*-Pr_3P)Ru$(NCCH_3)_2$]BAF (BAF=[$B(C_6F_5)_4$]) reported by Nikonov and co-workers.[77] Simple alkyl and aryl nitriles were easily converted at room temperature into the corresponding N-silylimines. Excellent chemoselectivity could be observed in the presence of C=C and C=O functional groups. TOF's of up to 75 h^{-1} were realized in this transformation.

1.7. Claisen-Tishchenko Reaction of Aldehydes

Ester synthesis and hydrogenation of organic substrates are among the many fundamental transformations of fine chemical industry. The atom economic Claisen-Tishchenko disproportionation of aldehydes to the corresponding carboxylic esters[78] has acquired wide attention due to their application in food, polymer, dye and perfume industry.[79] Traditional catalysts for this reaction include mainly sodium[80] and particularly aluminium alkoxides.[81] Various transition metal and lanthanoid compounds are reported to be active for Claisen-Tishchenko reaction, one of the notable candidate among them is the transition metal Rh^{III} hydrido complex [Rh$(PhBP_3)(H)_2(CH_3CN)$], reported by Tejel and co-workers, which with applying 1 mol% at room temperature furnished the corresponding esters upto quantitative yield in 1 min. (TOF: 6000 h^{-1}).[82] Recently, this disproportionation reaction between two different selected aldehydes could be accomplished in good selectivities using a metal complex of Ni.[83] The key step involved in Claisen-Tishchenko reaction is the hydride transfer from one molecule of aldehyde to another molecule of aldehyde and subsequent coupling between the two species. Thus, one can expect that metal complexes capable of performing

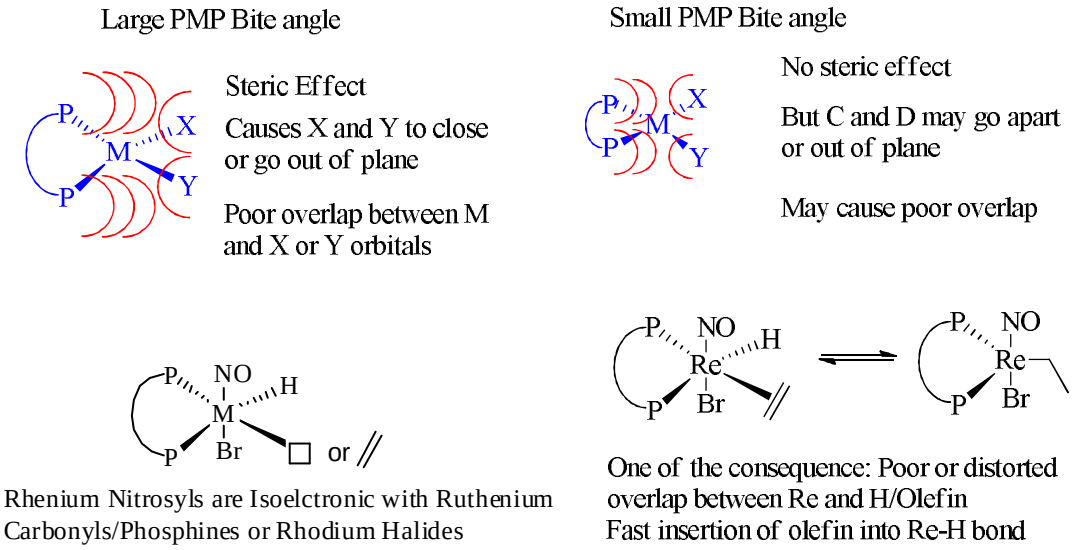
the transfer hydrogenation reactions can often also catalyze the disproportionation reactions of aldehydes to the corresponding carboxylic esters.

1.8. Goal of the Project

The area of homogeneous hydrogenations is dominated by platinum group metals.[6a] Due to their toxicity, the precious metal components after the catalysis are to be removed from the active pharmaceutical ingredients in industrial processes.[84] Also, due to their scarcity and high cost, these catalysts need to be recycled. Precious metal catalysis often suffers from reduction to the metals under hydrogenation conditions resulting in loss of catalytic activity.[85] Being border to the precious metals in the periodic table, the element rhenium is expected to show some of the precious metal's character. This is revealed in their interaction with H_2[86] and olefins.[87] The most active catalytic homogeneous hydrogenation and related reactions consists of generally ruthenium phosphine or carbonyl or rhodium halide fragments.[6] A rhenium nitrosyl fragment is isoelectronic with them. These properties made us believe that suitable rhenium complexes could be efficient catalysts for hydrogenation and other related reactions.

Nitrosyl ligand can supports different oxidation states of metal centers often accompanied by different coordination modes.[19,88] Furthermore it exerts a relatively strong *trans*-effect, leading to activation of metal−ligand bonds. One of the latter influences is nitrosyl-substituted transition metal hydrides in which the M−H bonds show increased hydridic character.[19,88] Halogen ligands like a bromide are good π-donors and disposing them *trans* to the strong π-acceptor NO ligand would exert a stabilizing strong push pull π-interaction which would leads to the other *cis* ligands labile.[89]

Diphosphines are often applied as ligands with precious metals active for hydrogenation and related reactions.[90] The PMP angle in a metal diphosphine complex termed as 'bite



Scheme 1.12. Influence of bite angle on steric and electronic factors.

angle' can have an influence on the steric and electronic factors - a ligand tuning would help

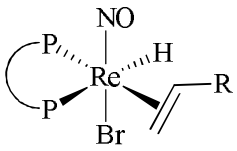
angle' can have an influence on the steric and electronic factors - a ligand tuning would help

to increase the efficiency of the catalyst.[91] A wide bite angle of the ligands induces a distortion from the octahedral geometry that can lead to poor orbital overlap between the metal and the bound atoms (Scheme 1.12). A small bite angle ligand, though generally not hindered, can also lead to poor orbital overlapping of the bound atoms attached with metal centre due to the distortion.

The Xantphos family of ligands are often used in many catalytic transformations, particularly in hydroformilation reactions.[91,92] Also, silicon containing compounds are usually found to have high stability. 4,6-Bis(diphenylphosphino)-10,10-dimethylphenoxasilin (Sixantphos)[92] a diphosphine ligand belonging to the xantphos family of ligands bearing a silicon back bone having a large bite angle of 108° would be a suitable choice for the preparation of the catalyst. Complexes bearing other large bite angle diphosphines; the new derivative of Sixantphos ligand 4,6-Bis(diphenylphosphino)-10,10-diphenylphenoxasilin

(Sixantphos-Ph_2) as well as one with a sulfur backbone 4,6-bis(diphenylphosphino)phenoxathiin (Thixantphos) were also prepared.

The classical well known Wilkinson or Osborn type catalysis consists of a metal hydride and a η^2-olefin/vacant site coordination during the catalytic cycle. The actual hydrogenation of these catalytic cycles starts at this state by the insertion of olefin into the M-H bond. Thus, preparation of the catalytic active species or a species much closer to the active species would certainly be one of the best choices to start with. Keeping these in mind, we have targeted the synthesis of appropriate nitrosyl rhenium complexes bearing large bite angle Sixantphos ligand with ethylene and a H *cis* to each other and both *trans* to the diphosphine and a bromide in the other position *trans* to the NO ligand (Scheme 1.13).



Scheme 1.13. Type of target Re(I) complexes for catalytic hydrogenation and related reaction.

1.9. References

1. "Recognizing the Best in Innovation: Breakthrough Catalyst". *R&D Magazine*, Sep. **2005**, p. 20.
2. a) G. J. Kubas , R. R. Ryan , B. I. Swanson , P. J. Vergamini, H. J. Wasserman *J. Am. Chem. Soc*. **1984**, *106*, 451-452; b) Kubas, G. J. *Metal Dihydrogen and σ-Bond Complexes: Structure, Theory, and Reactivity*, Kluwer, New York, **2001**; (c) Kubas, G. J. *Chem. Rev*. **2007**, *107*, 4152.
3. (a) M. J. S. Dewar, *Bull. Soc. Chim. Fr*. **1951**, *18*, C79; b) J. Chatt, L. A. Duncanson, *J. Chem. Soc*. **1953**, 2929; c) R. E. Harmon, S. K. Gupta, D. J. Brown, *Chem. Rev*. 1973, *73*, 21-52; d) Kubas, G. J. *J. Organometal. Chem*. **2001**, *635*, 37.
4. a) P. G. Jessop, R. H. Morris, *Coord. Chem. Rev*. **1992**, *121*, 155-284. b) D. M. Heinekey, W. J. Jr. Oldham, *Chem. Rev*. **1993**, *93*, 913-926.
5. a) R. H. Morris, *Can. J. Chem*. **1996**, *74*, 1907. b) G. Jia, C. P. Lau, *Coord. Chem. Rev*. **1999**, *83*, 190-192.
6. a) J. G. de Vries, C. J. Elsevier, in *Handbook of Homogeneous Hydrogenation*; Eds.; Wiley-VCH: Weinheim, **2007**; b) S. E. Clapham, A. Hadzovic, R. H. Morris, *Coord. Chem. Rev*. **2004**, *248*, 2201-2237.
7. a) M. Calvin, *Trans. Far. Soc*. **1938**, *34*, 1181; b) M. Calvin, *J. Am. Chem. Soc*. **1939**, *61*, 2230.

8. a) S. S. Bath, L. Vaska, *J. Am. Chem. Soc*. **1965**, *85*, 3500; b) L. Vaska, *Inorg. Nucl. Chem. Lett*. **1965**, *1*, 89.
9. a) D. Evans, G. Yagupsky, G. Wilkinson, *J. Chem. Soc*. *A* **1968**, 2660; b) M. Yagupsky, C.K. Brown, G. Yagupsky, G. Wilkinson, *J. Chem. Soc. A* **1970**, 937; c) C. O'Connor, G. Yagupsky, D. Evans, G. Wilkinson, *Chem. Commun*. **1968**, 420; d) C. O'Connor, G. Wilkinson, *J. Chem. Soc. A* **1968**, 2665; e) G. Yagupsky, G. Wilkinson, *J. Chem. Soc. A* **1970**, 941; f) D. Evans, J. A. Osborn, G. Wilkinson, *J. Chem. Soc. A* **1968**, 3133; g) G. Yagupsky, C. K. Brown, G. Wilkinson, *Chem. Commun*. **1969**, 1244; h) G. Yagupsky, C. K. Brown, G. Wilkinson, *J. Chem. Soc*. *A* **1970**, 1392; i) C. K. Brown, G. Wilkinson, *J. Chem. Soc. A* **1970**, 2753.
10. a) J. A. Osborn, G. Wilkinson, J. F. Young, *Chem. Commun*. **1965**, 17; b) J. A. Osborn, F. H. Jardine, J. F. Young, G. Wilkinson, *J. Chem. Soc*. *A* **1966**, 1711; c) M. A. Bennett, P. A. Longstaff, *Chem. Ind. (London)* **1965**, 846; d) R. S. Coffey, British Patent 1121642, **1965**; e) L. Vaska, R. E. Rhodes, *J. Am. Chem. Soc*. **1965**, *87*, 4970.
11. L. Vaska, D. Rhodes, *J. Am. Chem. Soc*. **1965**, *87*, 4970.
12. J. M. Brown, P. A. Chaloner, In *Homogeneous Catalysis with Metal Phosphine Complexes*, Pignolet, L.H. (Ed.), Plenum Press, New York, **1983**, Ch 4.
13. J. Halpern, J. F. Harrod, B. R. James, *J. Am. Chem. Soc*. **1961**, *83*, 753.
14. D. Evans, J. A. Osborn, F. H. Jardine, G. Wilkinson, *Nature* **1965**, *208*, 1203.
15. P. S. Hallman, B. R. McGarvey, G. Wilkinson, *J. Chem. Soc*. *A* **1968**, 3143.
16. Joshi, A. M., Macfarlane, K. S., James, B. R., *J. Organomet. Chem*. **1995**, *488*, 161.
17. a) C. O'Connor, G. Yagupsky, D. Evans,G. Wilkinson, *Chem. Commun*. **1968**, 420; b) C. O'Connor, G. Wilkinson, *J. Chem. Soc. A* **1968**, 2665.
18. a) Y. Jiang, J. Hess, T. Fox, H. Berke, *J. Am. Chem. Soc*. **2010**, *132*, 18233-18247. b) Y. Jiang, B. Schirmer, O. Blacque, T. Fox, S. Grimme, H. Berke, *J. Am. Chem. Soc*. **2013**, *135*, 4088-4102; c) Crabtree, R. H. *Acc. Chem. Res*. **1979**, *12*, 331.
19. a) R. R. Schrock, J. A. Osborn, *J. Am. Chem. Soc*. **1976**, *98*, 2134; b) R. R. Schrock, J. A. Osborn, *J. Am. Chem. Soc*. **1976**, *98*, 4450; c) R. H. Crabtree, A. Gautier, G. Giordano, and T. Khan, *J. Organometal. Chem*. **1977**, *141*, 113.
20. R. H. Crabtree, H. Felkin, and G. E. Morris, *J. Organometal. Chem*. 1977, *141*, 205.
21. W.S. Knowles, M. J. Sabacky, *Chem. Commun*. **1968**, 1445.
22. a) L. Horner, H. Siegel, H. Büthe, *Angew. Chem*. **1968**, *80*, 1034; b) *Angew. Chem., Int. Ed. Engl*. **1968**, *7*, 942.
23. a) H.U. Blaser, F. Spindler, M. Studer, *Appl. Catal. A: Gen.* 2001, 119-143 b) W.S. Knowles, *Chem. Ind. (Dekker)*, 1996, *68*, 141; c) W.S. Knowles, *Acc. Chem. Res*. 1983, *16*, 106. d) W.S. Knowles, *J. Chem. Ed*. **1986**, *63*, 222. e) R. Schmid, M. Scalone, in: E. N. Jacobsen, H. Yamamoto, A. Pfaltz (Eds.), Comprehensive Asymmetric Catal. Springer, Berlin, 1999, p. 1439.
24. R. S. Coffey, *J. Chem. Soc. Chem. Commun*. **1967**, 923.
25. W. Strohmeier, H. Steigerwald, *J. Organomet. Chem.* **1977**, *129*, 43.
26. W. Strohmeier, L. Weigelt, *J. Organomet. Chem.* **1978**, *145*, 189.

27. R. A. Sanchez-Delgado, A. Andriollo, O.L. De Ochoa, T. Suarez, N. Valencia, *J. Organomet. Chem.* **1981**, *209*, 77.
28. R. A. Sanchez-Delgado, A. Andriollo, N. Valencia, *J. Mol. Catal.* **1984**, *24*, 217.
29. G. Mestroni, G. Zassinovich, A. Camus, *J. Organomet. Chem.* **1977**, *140*, 63.
30. G. Mestroni, R. Spogliarich, A. Camus, F. Martinelli, G. Zassinovich, *J. Organomet. Chem.* **1978**, *157*, 345.
31. R. Noyori, T. Ohkuma, *Angew. Chem. Int. Ed. Engl*. **2001**, *40*, 40.
32. T. Ohkuma, H. Ooka, S. Hashiguchi,T. Ikariya, R. Noyori, *J. Am. Chem. Soc.* **1995**, *117*, 2675.
33. (a) H. Doucet, T. Ohkuma, K. Murata, T. Yokozawa, M. Kozawa, E. Katayama, A. F. England, T. Ikariya, R. Noyori, *Angew. Chem.* **1998**, *110*, 1792-1796.
34. Linn, D.E., Halpern, J., *J. Am. Chem. Soc.* **1987**, *109*, 2969.
35. L. Mark′o, J. Bakos, *J. Organomet. Chem.* **1974**, *81*, 411.
36. V. I. Tararov, R. Kadyrov, T.H. Riermeier, A. Borner, *J. Chem. Soc. Chem. Commun*. **2000**, 1867.
37. T. Gross, A.M. Seayad, M. Ahmad, M. Beller, *Org. Lett*. **2002**, *4*, 2055.
38. D. E. Fogg, B. R. James, In: *Catalysis of Organic Reactions of the Chemical Industry*. *Dekker*, **1995**, *62*, 435.
39. K. S. Macfarlane, I. S. Thorburn, P. W. Cyr, D. Chau, S. J. Rettig, B. R. James, *Inorg. Chim. Acta* **1998**, *270*, 130.
40. R, Abbel, K. Abdur-Rashid, M. Faatz, A. Hadzovic, A. J. Lough, R. H. Morris, *J. Am. Chem. Soc*. **2005**, *127*, 1870.
41. K. Abdur-Rashid, A. J. Lough, R. H. Morris, *Organometallics* **2001**, *20*, 1047.
42. H. U. Blaser, H. P. Buser, K. Coers, R. Hanreich, H. P. Jalett, E. Jelsch, B. Pugin, H. D. Schneider, F. Spindler, A. Wegmann, Chimia **1999**, *53*, 275.
43. a) R. A. Grey, G. P. Pez, A. Wallo, J. Am. Chem. Soc. 1981, 103, 7536 – 7542; b) T. Yoshida, T. Okano, S. Otsuka, *J. Chem. Soc., Chem. Commun.* **1979**, 870 – 871.
44. a) S. Gomez, J. A. Peters, T. Maschmeyer, *Adv. Synth. Catal*. **2002**, *344*, 1037-1057; b) B. Chen, U. Dingerdissen, J. G. E. Krauter, H. G. J. L. Rotgerink, K . Mobus, D. J. Ostgard, P. Panster, T. H. Riermeier, S. Seebald, T. Tacke, H. Trauthwein, *Appl. Catal. A: Gen*. **2005**, 280, 17-46; c) R. Reguillo, M. Grellier, N. Vautravers, L. Vendier, S. Sabo-Etienne, *J. Am. Chem. Soc*. 2010, 132, 7854-7855; d) J. von Braun, G. Blessing, F. Zobel, *Ber. Dtsch. Chem. Ges.* **1923**, 56, 1988-2001; e) G. Mignonac, *Comptes Rendus* **1920**, *171*, 14.
45. a) S. Enthaler, D. Addis, K. Junge, G. Erre, M. Beller, *Chem. Eur. J*. **200**8, *14*, 9491-9494.
46. R. Reguillo, M. Grellier, N. Vautravers, L. Vendier, and S. Sabo-Etienne, *J. Am. Chem. Soc*. *2010, 132*, 7854–7855
47. D. Srimani, M. Feller, Y. Ben-David, D. Milstein, *Chem. Commun*. **2012**, *48*, 11853-11855.
48. R. A. Grey, G.P. Pez, A. Wallo, *J. Am. Chem. Soc.* **1981**, *103*, 7536.
49. E. Balaraman, C. Gunanathan, J. Zhang1, L. J. W. Shimon, D. Milstein, *Nat. Chem.* **2011**, *3*, 609-614.
50. W. N. O. Wylie, R. H. Morris, *ACS Catal*. **2013**, *3*, 32-40.
51. *IPCC Fourth Assessment Report: Climate Change 2007: Synthesis Report; Ch. 2.2.*

52. *Annual Energy Review 2011; U.**S**. Energy Information Administration: Washington, DC, 2012; Table 11.1, pp 302-303.*
53. *USGS World Petroleum Assessment 2000 and US DOE IEA 1999, World Energy Overview.*
54. N. S. Lewis, D. G. Nocera, *Proc. Natl. Acad. Sci*. **2006**, *103*, 15729.
55. a) K. Ushikoshi, K. Mori, T. Watanabe, M. Takeuchi, M. Saito, *Stud. Surf. Sci. Catal*. **1998**, *114*, 357; b) M. Saito, *Catal. Surv. Jpn*. **1998**, 175. c) L. C. Grabow, M. Mavrikakis, *ACS Catal*. **2011**, *1*, 365.
56. a) Iyad Karamé. *Hydrogenation*; Ch *10*: InTech: Rijeka, Croatia, 2012. (b) P. G. Jessop, F. Joó, F, C. -C. Tai, *Coord. Chem. Rev*. **2004**, *248*, 2425-2442. (c) W. Wang, S. Wang, X. Ma, J. Gong, *Chem. Soc. Rev*. **201**1, *40*, 3703-3727.
57. R. Tanaka, M. Yamashita, K. Nozaki, *J. Am. Chem. Soc*. **2009**, *131*, 14168-14169.
58. a) S. Chakraborty, J. Zhang, J. A. Krause, H. Guan, H. *J. Am. Chem. Soc.* **2010**, *132*, 8872; b) S. N. Riduan, Y. Zhang, J. Y. Ying, *Angew. Chem.* **2009**, *121*, 3372-3375; c) M.-A. Courtemanche, M.-A. Légaré, L. Maron, F.-G. Fontaine, *J. Am. Chem. Soc*. **2013**, *135*, 9326-9329.
59. C. A. Huff, M. S. Sanford, *J. Am. Chem. Soc*. **2011**, *133*, 18122-18125.
60. S. Wesselbaum, T. vom Stein, J. Klankermayer, W. Leitner, *Angew. Chem., Int. Ed.* **2012**, *51*, 7499-7502.
61. A. Boddien, F. Grtner, C. Federsel, P. Sponholz, D. Mellmann, R.Jackstell, H. Junge, M. Beller, *Angew. Chem. Int. Ed*. **2011**, 50, 6411-6414.
62. C. Ziebart, C. Federsel, P.Anbarasan, R. Jackstell, W. Baumann, A.Spannenberg, M. Beller, *J. Am. Chem. Soc*. **2012**, *134*, 20701-20704.
63. H. Meerwein, R. Schmidt, *Justus Liebigs Ann. Chem.* **1925**, *444*, 221.
64. R.V. Oppenauer, *Recl. Trav. Chim. Pays-Bas* **1937**, *56*, 137.
65. For selected examples see; a) T. Naota, H. Takaya, S.-I. Murahashi, *Chem. Rev*. **1998**, *9*8, 2599; b) B. N. Chaudret, D. J. Cole-Hamilton, R.S. Nohr, G. Wilkinson, *J. Chem. Soc., Dalton Trans.* **1977**, 1546; c) H. Imai, T. Nishiguchi, K. Fukuzumi, *J. Org. Che*m. **1976**, *41*, 665: d) A. Aranyos, G. Csjernyik, K.J. Szabo, J.-E. Bäckvall, *Chem. Commun.* **1999**, 351; *ibid*, 2131; e) E. Mizushima, M. Yamaguchi, T. Yamagishi, *J. Mol. Catal. A* **1999**, *148*, 69; f) D. E. Linn, J. Halpern, *J. Am. Chem. Soc.* **1987**, *109*, 2969; g) P. A. Chaloner, M. A. Esteruelas, F. Joó, L. A. Oro, *Homogeneous Hydrogenation*, Kluwer Academic Publishers, Dordrecht, The Netherlands,**1994**, Ch. 3; h) E. Mizushima, M. Yamaguchi, T. Yamagishi, *Chem. Lett*. **1997**, *237*; i) Y. Nishibayashi, I. Takei, S. Uemura, M. Hidai, *Organometallics* **1999**, *18*, 2291; j) G. C. Jia, H. M. Lee, L. D. Williams, *J. Organomet. Chem*. **1997**, *534*, 173; k) J.-E. Bäckvall, *J. Organomet. Chem.* **2002**, *652*, 105. l) S. Bhaduri, K. Sharma, D. Mukesh, *J. Chem. Soc., Dalton Trans*. **1993**, *12*, 1191; m) C. S. Yi, Z. He, I. A. Guzei, *Organometallics* **2001**, *20*, 3641; n) O. Pàmies, J.-E. Bäckvall, *Chem. Eur. J*. **200**1, 7, 5052.
66. For selected examples, see; a) S. Hashiguchi, A. Fujii, J. Takehara, T. Ikariya, R. Noyori, *J. Am. Chem. Soc*. **1995**, *117*, 7562; b) J. X. Gao, T. Ikariya, R. Noyori, *Organometallics* **1996**, *15*, 1087; c) T. Ikariya, K. Murata, R. Noyori, *Org. Biomol. Chem*. **2006**, *4*, 393; d) R. Noyori, S. Hashiguchi, *Acc. Chem. Res*. **1997**, *30*, 97.

67. For selected examples, see; a) Y. Shvo, D. Czarkie, *J. Organomet. Chem*. **1986**, *31*5, 25; b) Y. Blum, D. Czarkie, Y. Rahamim, Y. Shvo, *Organometallics* **198**5, *4*, 1459; c) B. L. Conley, M. K. Pennington-Boggio, E. Boz, T. J. Williams, *Chem. Rev*. **201**0, *110*, 2294; d) C. P. Casey, S. W. Singer, D. R. Powell, R. K. Hayashi, M. Kavana, *J. Am. Chem. Soc*. **2001**, *123*, 1090; e) N. Menashe, Y. Shvo, *Organometallics* **1991**, *10*, 3885; c) N. Menashe, E. Salant, Y. Shvo, *J. Organomet. Chem*. **1996**, *514*, 97; f) C. P. Casey, S. W. Singer, D. R. Powell, R. K. Hayashi, M. Kavana, *J. Am. Chem. Soc*. **2001**, *123*, 1090; g) N. Menashe, Y. Shvo, *Organometallics* **1991**, *10*, 3885; h) N. Menashe, E. Salant, Y. Shvo, *J. Organomet. Chem*. **1996**, *514*, 97. i) A. Landwehr, B. Dudle, T. Fox, O. Blacque, H. Berke, *Chem. Eur. J*. **2012**, *18*, 5701-5714.
68. a) M. Yamakawa, H. Ito, R. Noyori, *J. Am. Chem. So*c. **2000**, *122*, 1466; b) H. P. Dijkstra, M. Albrecht, S. Medici, G. P. M. van Klink, G. van Koten, *Adv. Synth. Catal*. **2002**, *344*, 1135; c) T. Yamagishi, E. Mizushima, H. Sato, M. Yamachi, *Chem. Lett*. **1998**, 1255.
69. a) N.C. Deno, H.J. Peterson, G. S. Saines, *Chem. Rev*. **1960**, *60*, 7; b) G. Brieger, T. J. Nestrick, *Chem. Rev*. **1974**, *74*, 567; c) R. A. W. Johnstone, A. H. Wilby, I. D. Entwistle, *Chem. Rev*. **1985**, *85*, 129; d) P. A. Chaloner, M.A. Esteruelas, F. Joó, L. A. Oro, *Homogeneous hydrogenation*. Kluwer Academic Publishers, Dordrecht, Boston, London, **1994**, Ch. 3, p. 87 & 183; e) S. Gladiali, G. Mestroni, Transfer hydrogenations. In: M. Beller, C. Bolm (Eds.), *Transition Metals for Organic Synthesis*. Wiley-VCH, Weinheim, New York, Chichester, Brisbane, Singapore, Toronto, **1998**, Ch. 3, p. 97.
70. S. Werkmeister, C. Bornschein, K. Junge, M. Beller, *Chem. Eur. J*. **2013**, *19*, 4437-4440.
71. S. Werkmeister, C. Bornschein, K. Junge, M. Beller, *Eur. J. Org. Chem*. **2013**, 3671-3674.
72. a) *Hydrosilylation, Advances in Silicon Science* (Ed.: B. Marciniec), Springer, Berlin, **2009**; b) A. K. Roy, *Adv. Organomet. Chem*. **2008**, *55*, 1; c) S. E. Gibson, M. Rudd, *Adv. Synth. Catal*. **2007**, *349*, 781; d) B. Marciniec, *Appl. Organomet. Chem*. **2000**, *14*, 527; e) R. Noyori, *Asymmetric Catalysis in Organic Synthesis*, Wiley, New York, **1994**; f) I. Ojima, *Catalytic Asymmetric Synthesis*, VCH, New York, **1993**; g) H. Brunner, W. Zettimeier, *Handbook of Enantioselective Catalysis with Transition Metal Compounds*, VCH, Weinheim, **1993**; h) I. Ojima, *The Chemistry of Organic Silicon Compounds* (Eds.: S. Patai, Z. Rappoport), Wiley, New York, **1989**, ch. 25.
73. a) M. Ochiai, H. Hashimoto, H. Tobita, *Angew. Chem*. **2007**, *119*, 8340; b) R. Calas, *Pure Appl. Chem*. **1966**, *13*, 61; c) A. J. Chalk, *J. Organomet. Chem*. **1970**, 21, 207; d) R. J. P. Corriu, J. J. E. Moreau, M. Pataud-Sat, *J. Organomet. Chem*. **1982**, *228*, 301; e) B. Marciniec, *Comprehensive Handbook on Hydrosilylation*, Pergamon, Oxford, **1992**.
74. a) R. J. P. Corriu, J. J. E. Moreau, M. Pataud-Sat, *J. Organomet. Chem*. **1982**, *228*, 301; a) T. Murai, T. Sakane, S. Kato, *J. Org. Chem*. **1990**, *55*, 449-453; b) T. Murai, T. Sakane, S. Kato, *Tetrahedron Lett*. **1985**, *26*, 5145-5148; c) A. M. Caporusso, N. Panziera, P. Petrici, E. Pitzalis, P. Salvadori, G. Vitulli, G. Martra, *J. Mol. Catal. A* **1999**, *150*, 275-285.
75. R. Calas, E. Frainnet, A. Bazouin, *C. R. Hebd, Seances Acad. Sci*. **1961**, 252, 420-422.
76. a) T. Fuchigami, I. Igarashi, *Jpn Patent Appl. JP11228579*, **1999**; b) A. Y. Khalimon, R. Simionescu, L. G. Kuzmina, J. A. K. Howard, G. I. Nikonov, *Angew. Chem*. **2008**, 120, 7815; c) E. Peterson, A. Y. Khalimon, R. Simionescu, L. G. Kuzmina, J. A. K. Howard, G. I. Nikonov, *J. Am. Chem. Soc*. **2009**,

131, 908; d) J. Kim, Y. Kang, J. Lee, Y. K. Kong, M. S. Gong, S. O. Kang, J. Ko, *Organometallics* **2001**, 20, 937; e) M. Tanabe, K. Osakada, *Organometallics* **2001**, *20*, 2118; f) H. Hashimoto, I. Aratani, C. Kabuto, M. Kira, *Organometallics* **2003**, *22*, 2199; g) T. Watanabe, H. Hashimoto, H. Tobita, *J. Am. Chem. Soc*. **2007**, *128*, 2176;

77. D. V. Gutsulyak, Georgii I. Nikonov, *Angew. Chem*. **2010**, *122*, 7715-7718.
78. a) L. Claisen, *Ber. Dtsch. Chem. Ges.* **1887**, 20, 646-650; b) W. Tischtschenko, *Chem. Zentralbl*. **1906**, *77*, 1309-1311; c) T. Seki, T. Nakajo, M. Onaka, *Chem. Lett*. **2006**, *35*, 824-829; d) M. H. S. A. Hamid, P. A. Slatford, J. M. J. Williams, *Adv. Synth. Catal*. **2007**, *349*, 1555-1575; e) K. Ekoue-Kovi, C. Wolf, *Chem. Eur. J*. **2008**, *14*, 6302-6315; f) W. I. Dzik, L. J. Gooßen, *Angew. Chem.* **2011**, *123*, 11241-11243.
79. *Ullmann's Encyclopadia of Industrial Chemistry*, 6th edn., Wiley-VCH, Weinheim, **2002**.
80. a) O. Kamm,W. F. Kamm, *Org. Synth. Coll. Vol. 1*, **1941**,104; b) F. W. Swamer, C. R. Hauser, *J. Am. Chem. Soc*. **1946**, *68*, 2647-2649.
81. a) W. C. Child, H. Atkins, *J. Am. Chem. Soc*.**1923**, *45*, 3013-3023; d) Y. Ogata, A. Kawasaki, *Tetrahedron* **1969**, *25*, 929-935; e) T. Ooi, T.Miura, K. Takaya, *Tetrahedron Lett*. 1999, *40*, 7695–7698; f) I. Simpura, V. Nevalainen, *Tetrahedron* 2001, *57*, 9867-9872; g) T. Ooi, K. Ohmatsu, K. Sasaki, T. Miura, K. Maruoka, *Tetrahedron Lett.* 2003, *44*, 3191– 3193; h) P. R. Stupp, *J. Org. Chem*. 1973, *38*, 1433– 1434.
82. C. Tejel, M. A. Ciriano V. Passarelli, *Chem. Eur. J*. **201**1, *17*, 91–95.
83. W. I. Dzik, L. J. Gooßen, Angew. Chem. **2011**, 123, 11241–11243, Y. Hoshimoto, M. Ohashi, S. Ogoshi, *J. Am. Chem. Soc*. **2011**, *133*, 4668-4671.
84. a) Zimmermann, S.; Sures, B. *Environ. Sci. Pollut. Res.* **2004**, *11*, 194-199; b) M. Schmid, S. Zimmermann, H. F. Krug, B. Sures, *Environ. Int*. **2007**, *33*, 385-390.
85. a) D. Heller, A. H. M. Vries, in *Handbook of Homogeneous Hydrogenation*, (Eds.: J. G. de Vries, C. J. Elsevier), Wiley-VCH: Weinheim, 2007; pp 1483-1516; b) Bartholomew, C. H. *Appl. Catal. A* **2001**, *212*, 17-60; c) Widegren, J. A.; Finke, R. G. *J. Mol. Catal. A* Chem. **2003**, *198*, 317-341.
86. a) D. M. Heinekey, M. H. Voges, D. M. Barnhart, *J. Am. Chem. Soc*. **1996**, *118*, 10792–10802; b) C. Bianchini, A. Marchi, L. Marvelli, *J. Am. Chem. Soc*. **2011**, *133*, 8168-8178; c) M. Peruzzini, A. Romerosa, R. Rossi, A. Vacca, *Organometallics* **1995**, *14*, 3203-3215; c) D. Gusev, A. Llamazares, G. Artus, H. Jacobsen, H. Berke, *Organometallics* **1999**, *18*, 75-89.
87. a) A. Choualeb, O. Blacque, H. W. Schmalle, T. Fox, T. Hiltebrand, H. Berke, *Eur. J. Inorg. Chem.* **2007**, 5246-5261; b) J. A. Gladysz, B. J. Boone, *Angew. Chem., Int. Ed. Engl*. **199**7, *36*, 550-583.
88. a) H. Berke, P. Burger, *Comments Inorg.Chem.* **1994**, *16*, 279-312; b) H. Jacobsen, H. Berke, in *Recent Advances in Hydride Chemistry*; (Ed.: R. Poli), Elsevier: Amsterdam, Holland, **2001**; pp 89-116; c) A. Choualeb, E. Maccaroni, O. Blacque, H. W. Schmalle, H. Berke, *Organometallics* **2008**, *27*, 3474-3481.
89. J. Chatt, S. Coffey, *J. Chem. Soc. A* **196**9, 1963–1969.
90. M. L. Clarke, J. J. R. Frew, *Ligand electronic effects in homogeneous catalysis using transition metal complexes of phosphine ligands*; *Organometallic Chemistry*, **2009**, *35*, 19-46.

91. P. W. N. M. van Leeuwen, *Homogeneous Catalysis: Understanding the Art*, Kluwer Academic Publishers, The Netherlands, **2004**.
92. M. Kranenburg, Y. E. M. van der Burgt, P. C. J. Kamer, P. W. N. M. van Leeuwen *Organometallics* **1995**, *14*, 3081-3089.

Large Bite Angle Diphosphine Nitrosyl Rhenium Complexes as Highly Efficient Catalysts for Olefin Hydrogenations

(Part of this work is published in a) B. Dudle, K. Rajesh, O. Blacque, H. Berke, *Organometallics.* **2011**, *30*, 29862992; b) B. Dudle, K. Rajesh, O. Blacque, H. Berke, *J. Am. Chem. Soc.* **2011**, *133*, 8168-8178)

2.1. Introduction

The area of homogeneous hydrogenations is dominated by platinum group metals.[1] Due to their toxicity, the precious metal components are to be removed after catalysis from the active pharmaceutical ingredients in industrial processes.[2] Also, due to their scarcity and high cost, these catalysts need to be recycled. Precious metal catalysis often suffers from reduction to the metals under hydrogenation conditions resulting in loss of catalytic activity.[3] Being border to the precious metals in the periodic table, the element rhenium is expected to show some of the precious metal's character. This is revealed in their interaction with H_2[4] and olefins.[5] The most active catalytic homogeneous hydrogenation and related reactions consists of ruthenium generally phosphine or carbonyl or rhodium halide fragments.[1,6] A rhenium nitrosyl fragment is isoelectronic with these fragments. These properties made us believe that suitable rhenium complexes could be efficient catalysts for hydrogenation and other related reactions.

Our research group has accumulated considerable experience in the realm of rhenium nitrosyl chemistry, and we could recently demonstrated that *trans*-[$ReH_2(\eta^2$-ethylene)$(NO)(PR_3)_2$] (R = *i*-pr, cy) complexes catalyze the hydrogenation of simple olefins and ketones,[7] as well as hydrogen-related reactions, such as hydrosilylations, dehydrogenative silylations,[8] and dehydrogenative aminoborane coupling reactions.[9] Later during the progress

of our work, our group has come up with highly efficient hydrogenations of olefins using catalytic systems consisting of the above mentioned mono phosphine complexes along with suitable co-catalysts.[10] We expected improvement of the catalytic performance of these complexes by forcing the phosphines into *cis* positions by applying chelating diphosphines.

The nitrosyl ligand can supports different oxidation states of metal centers often accompanied by different coordination modes.[11,12] Furthermore it exerts a relatively strong *trans*-effect, leading to activation of the respective metal-ligand bonds. One of the latter influences is nitrosyl-substituted transition metal hydrides, in which the M−H bonds show increased hydridic character.[11,12] Halogen ligands, like a bromide, are perfect π-donors and disposing them *trans* to the strong π-acceptor NO ligand would exert a stabilizing strong push pull π-interaction, which may lead to labilization of *cis* ligands.[13]

Diphosphines are often applied as ligands in combination with precious metals active for hydrogenation and related reductive reactions.[14] The PMP angle (M = metal) in a metal diphosphine complex is termed as 'bite angle' which can have great influence on the steric and electronic properties and allows ligand tuning increasing the efficiency of the catalyst.[15] A large bite angle of the ligands induces a distortion of the complexes mainly labilizing neighbouring ligands from an octahedral geometry that can lead to not only poorer orbital overlap between the metal and the bound atoms, but also to higher steric pressure.

The Xantphos family of ligands are often used in many catalytic transformations, particularly in hydroformilation reactions.[15,16a] 4,6-Bis(diphenylphosphino)-10,10-dimethylphenoxasilin (Sixantphos) (**A**),[16a] a diphosphine ligand belonging to the xantphos family of ligands bearing a silicon back bone with a large bite angle of 109°, the new derivative of Sixantphos ligand 4,6-Bis(diphenylphosphino)-10,10-diphenylphenoxasilin (Sixantphos-Ph_2) (**B**) as well as one with a sulfur atom in the backbone, 4,6-

bis(diphenylphosphino)phenoxathiin (Thixantphos) (**C**)[16] were chosen as typical ligands to test our catalytic hypotheses (Figure 2.1).

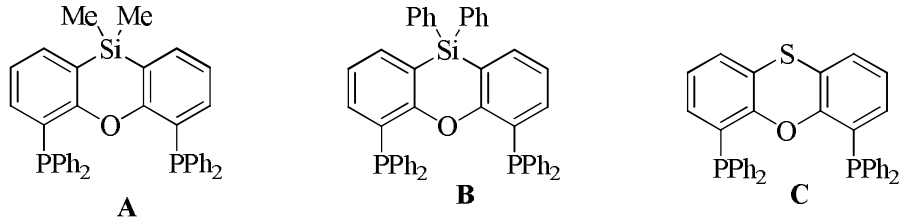


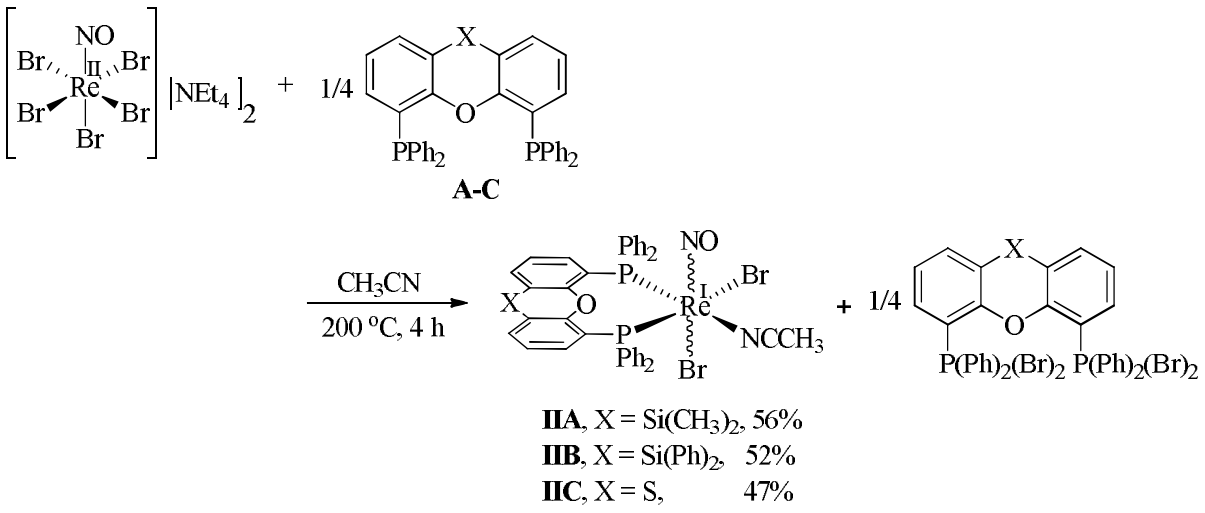
Figure 2.1. Diphosphine ligands **A**-**C** (P∩P).

2.2. Results and Discussion

2.2.1. Preparation of [Re(diphosphine)Br_2(NO)(CH_3CN)]

The Re(II) complex $[ReBr_5(NO)][NEt_4]_2$ (**I**),[17] obtained as per reported literature procedure was found to be a suitable precursor for the preparation of Re(I) diphosphine complexes.[18] The ligands Sixantphos (**A**) and Thixantphos (**C**) were also prepared according to literature procedures.[16] Following a similar procedure for the preparation of **A**, we also prepared the related, but previously unknown Sixantphos-Ph_2 compound (**B**).

The reduction of the Re(II) complex **I** in the presence of excess of the diphospines at a comparatively higher temperature of 200 °C in acetonitrile furnished the Re(I) complexes



Scheme 2.1. Preparation of Re(P∩P)Br_2(NO)(CH_3CN) complexes.

$[Re(P\cap P)(CH_3CN)Br_2(NO)]$ (**IIA-IIC**) in moderate yields (Scheme 2.1).

The reductions of the Re(II) to the Re(I) systems is facilitated by the oxidation of the excess of the respective ligand to RPR'_2Br_2 units. All these yellow coloured complexes **IIA-IIC** were stable in the solid state under ambient conditions.

Various constitutional and conformational isomers are possible for an octahedral complex bearing a rigid bidentate ligand.[19] The *trans* arrangement of the NO and one Br ligand is favoured due to a stabilizing strong "push-pull" π-interaction, making the diphosphine ligand to stay *cis* position to Br/NO axis.[20] The other two ligands CH_3CN and Br are thus disposed *cis* i.e., *trans* to the diphosphine P atoms. Therefore, only one type of constitutional isomer of **II** could be formed. The backbone of a rigid large bite angle diphosphine ligand could by no means be forced into the P-Re-P plane. Therefore, the backbone of these ligands adopts either geometries close to Br (denoted as **1**) or NO (denotes as **2**) or even 'twisted' conformations. At least **1**/**2** conformers are expected for a ligand with planar back bone and these in complex **IIA** are relative to the Br/NO axis.

Suitable crystals of the complex **IIA** were obtained when pentane was layered on a dichloromethane solution of it. The X-ray crystal structure of **IIA** showed a much distorted-octahedral structure with a *trans* Br/NO disorder crystallizes as a mixture of diastereomers **IIA1** and **IIA2** in a ratio of 86:14 and a *cis* diphosphine arrangement with respect to the Br/NO axis (Figure 2.2). The preference for isomers **1** or **2** seemed to be controlled by steric effect excerted by the diphosphine. The isomer **1** is favoured apparently avoiding van der Waals interaction of the Br ligand with one of the diphosphine phenyl groups with the closest $Br.....H_{Ph}$. This effect causes a slight tilting of the Br/NO axis in the up isomer **2**.

The bond lengths were found to be in the range of typical Re-Br, $Re-NCCH_3$, Re-P and Re-NO bonds. However, the large bite- angle diphosphine causes steric congestion in the

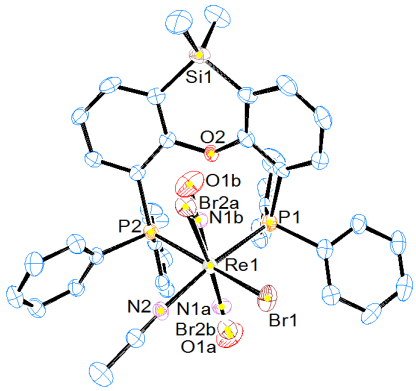
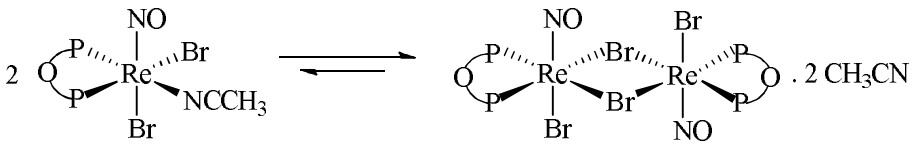


Figure 2.2. Molecular structure of complex **IIA** Anisotropic displacement parameters are depicted at the 50% probability level. Hydrogen atoms and solvent molecules are omitted for clarity. Selected bond lengths: Re1-P1: 2.405(1); Re2-P2: 2.443(1); Re1-Br1: 2.6090(5); Re1-Br2a: 2.5591(6); Re1-N2: 2.126(3); Re1N1a: 1.717(4). Selected bond angles: P1Re1P2:97.01(3)°; N2Re1Br1: 84.46(9)°; P1Re1Br1: 89.40(3)°; P2Re1P2: 89.54(9)°.

P-Re-P plane, which is reflected in the compression of the N2-Re-Br2 angle down to 84.46(9). The P-Re-P angle in **IIA** was found to be 97.01(3)°, despite the fact that Sixantphos (109°) possess substantially different natural bite angle.[16,21] To explain this deviation, one has to take into account that the reported natural bite angles[16] are determined by molecular dynamic simulations with a standard M-P distance of 2.3 Å. Since the actual Re-P distance in **IIA** is about 2.42 Å, the natural bite angles are systematically too low for rhenium complexes. The "corrected natural bite angles" would thus be 100°. Even if we consider this corrected value as a reference, it should be noted that there would still be deviations, which presumably originate from a high degree of conformational flexibility of the diphosphine backbones, as well as from thermodynamically very strong Re-P bonds, for which an optimal orbital overlap between the phosphorus atoms and the rhenium center is important.

The IR spectra of **IIA** displayed characteristic ν(NO) bands at 1680 and 1686 cm^{-1}. The ^{1}H NMR spectrum consists of broadened signals for the diphosphine and the CH_3CN ligands. Broad and overlapping signals were observed for bound and free CH_3CN. This points to the presence of dissociation equilibria at room temperature. The $^{31}P\{^{1}H\}$ NMR spectra consisted

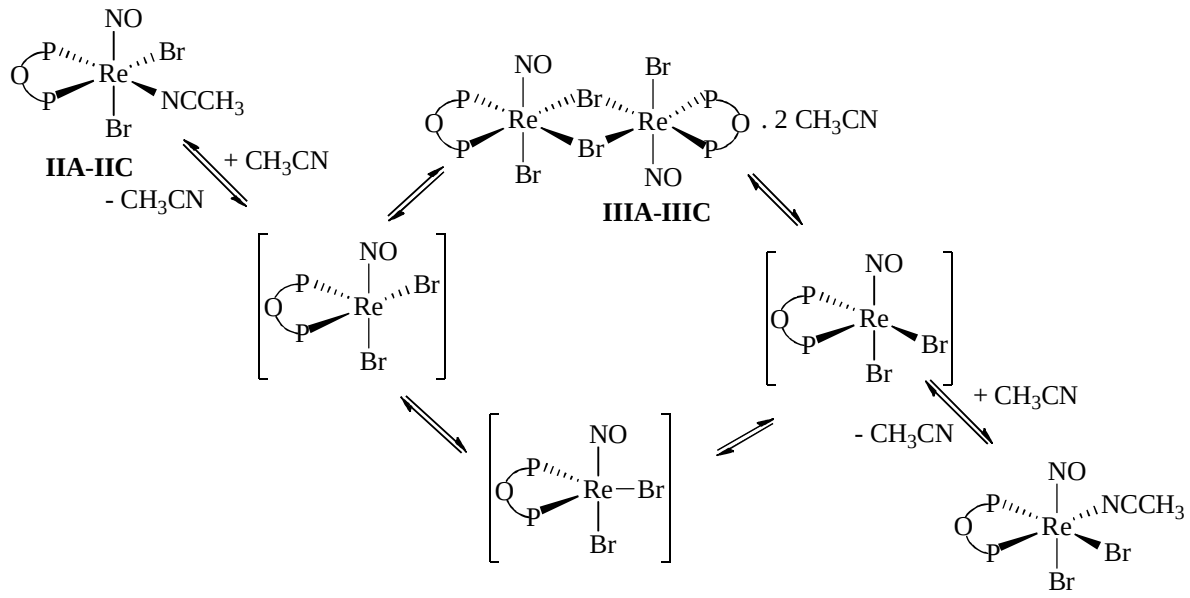
of two broad resonances, for which the coupling patterns could not be resolved. An additional $^{31}P\{^{1}H\}$ NMR signal became observable, which reduced upon addition of CH_3CN. Similar spectroscopic observations were made for complex **IIB** and **IIC**, which could be interpreted in terms of all these complexes [Re(**A**)Br_2(NO)(CH_3CN)] (**IIA**), [Re(**B**)Br_2(NO)(CH_3CN)] (**IIB**) and [Re(**C**)Br_2(NO)(CH_3CN)] (**IIC**) in solution were in equilibria with their bromo-bridged dimers [Re_2(**A**)$_2$$(Br)_2$(μ-Br)$_2$$(NO)_2$].2$CH_3CN$ (**IIIA**), [Re(**B**)$_2$$(Br)_2$(μ-Br)$_2$(NO].2$CH_3CN$ (**IIIB**) and [Re(**C**)$_2$$(Br)_2$(μ-Br)$_2$(NO)].2$CH_3CN$ (**IIIC**), respectively, expelling acetonitrile which were also found in their lattice (Scheme 2.2).[18] These processes were much less prominent in **IIB** and **IIC**. However, prolonged storage of **IIA** in the solid state for many days led this complex to stay as dinuclear complex **IIIA**. This equilibrium could be shifted considerably to the CH_3CN complex side by heating with CH_3CN.



IIA-C **IIIA-C**

Scheme 2.2. Bridging and splitting equilibria between complexes **IIA**-**IIC** and **IIIA**-**IIIC** respectively.

The CH_3CN dissociation is expected to be promoted by "steric pressure" imposed on this ligand by the large-bite-angle diphosphines. The broadness of the ^{1}H and the $^{31}P\{^{1}H\}$ NMR spectra and the absence of the expected coupling pattern of the $^{31}P\{^{1}H\}$ NMR signals can be explained by assuming dynamics with exchange of the inequivalent ^{31}P nuclei at a rate in the range of the NMR time scale. This exchange might proceed via either formation of μ^2-Br intermediates, which is assumed to be cleaved randomly, or via the formation of a transient unsaturated trigonal bipyramidal intermediate, which can rebind the freed CH_3CN at



Scheme 2.3. Mono- and dinuclear racemization pathways of **IIA-C** for the Br/CH_3CN exchange.

both sides of the Br ligand with equal probability (Scheme 2.3). To gain further insight into the dynamics, we recorded the $^{31}P\{^1H\}$ spectra of **IIA** at low temperature, thus slowing down the exchange processes. The room-temperature spectrum of a solution of **IIA** in $CDCl_3$ consisted of two broad signals at 1.0 and -4.0 ppm assigned to **IIA** and a sharp signal at 26.1 ppm assigned to **IIIA**. Warming the sample to 320 K leads to a significant broadening of the signal of **IIIA** at 26.1 ppm. At the same time the two signals of **IIA** collapsed into a

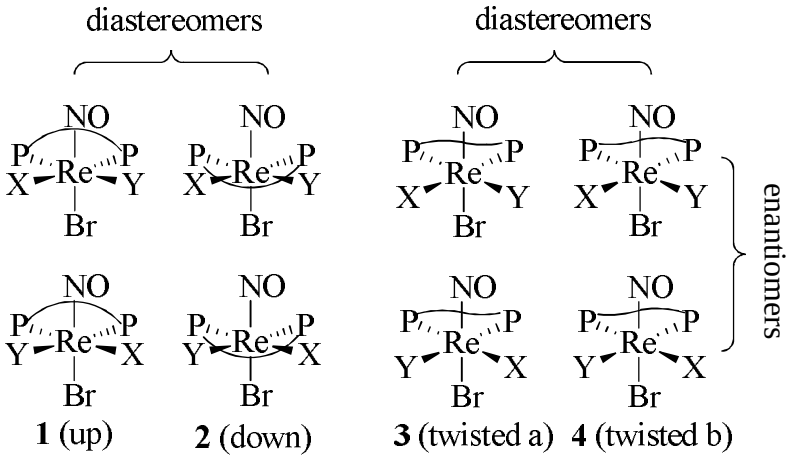
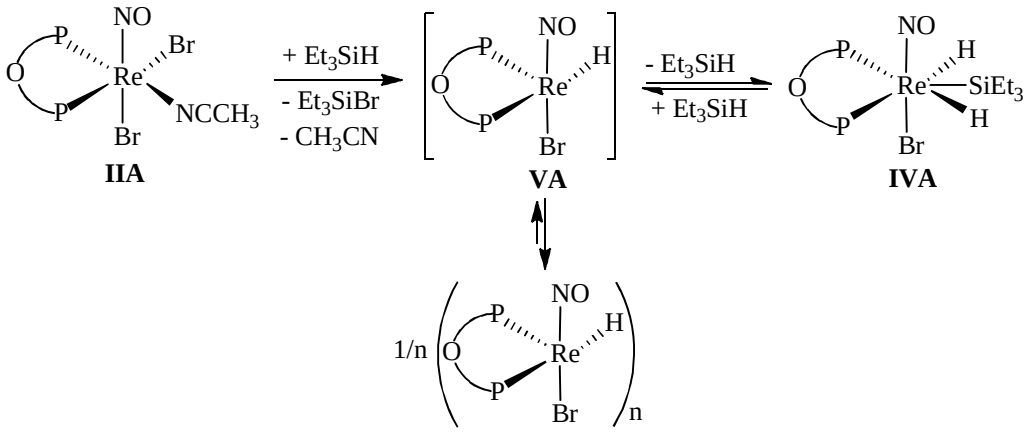


Figure 2.3. General sketch for isomerism in Re(P∩P)XY(Br)(NO) complexes

coalescing signal at -5.2 ppm. Cooling a sample of **IIA** to 240 K led to a sharp signal for **IIIA** at 26.0 ppm (0.08 P) and to four sets of doublets for **IIA** at 4.7 and 0.1 ppm (0.10 P), at 0.3 and -3.4 ppm (2JPP = 10Hz, 0.66 P), at -3.7 and -11.4 ppm (0.04 P), and at -7.2 and -14.1 ppm (0.12 P). From these results we can conclude that different conformers are present in solution. Four conformers are distinguishable with prevailing amounts of **IIA1**, which would be in accord with the results of the crystallographic analysis of this complex. Minor signals were assigned to **IIA2**, **IIA**(**twisted-a**) and **IIA** (**twisted-b**) (Figure 2.3). At room temperature these conformers are in fast exchange on the NMR time scale. An additional exchange is observed between **IIA** and **IIIA** at elevated temperatures, indicating that the isomerization pathway via the μ^2-Br dimers is operative in this case (Scheme 3).

2.2.2. Reaction of IIA-IIB and IIIA with Et_3SiH

Analogous complexes of type **II** or **III** bearing other diphosphines upon reaction with Et_3SiH dihydride silyl complexes $[ReBr(H)_2(SiEt_3)(NO)(P\cap P)]$ (**IV**), for which a pentagonal-bipyramidal structure is assumed with the hydrides, the silyl moiety, and the diphosphine all in the pentagonal plane, in close analogy to one of the structurally fully characterized $[ReBr(H)_2(SiMe_3)(NO)(P\cap P)]$, P∩P = 1,1'-bis(diphenylphosphino)ferrocene.[17] When this reaction of Et_3SiH with **II**A or **IIIA** or with a mixture of both was carried out, mixture of



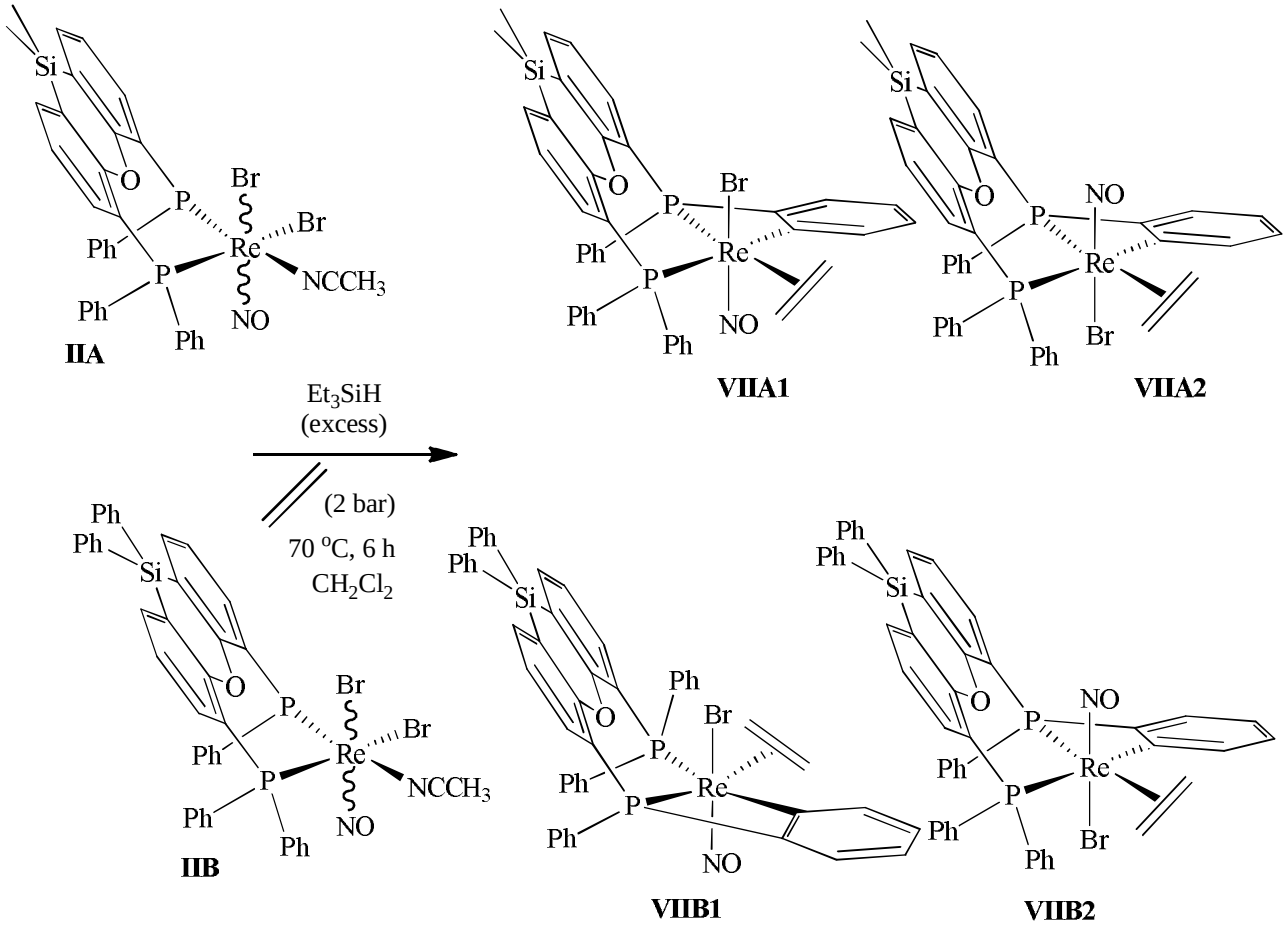
Scheme 2.4. Reaction of **IIA** with Et_3SiH.

products were observed, which could not be separated. According to NMR studies, we propose that at least one of the products has a silyl dihydride structure related to **IV**. Like few of the analogous complexes of **IV** bearing other diphosphines,[18] this complex was found to be stable in solution, but only in the presence of the silane. Attempts to isolate it led to the formation of a brick red precipitate similar to the cases of attempted isolation of other complexes **IV**,[18] from which we concluded that **IVA** is in equilibrium with the 16e complex [Re(**A**)HBr(NO)] (V) and Et_3SiH, which subsequently may oligomerize to μ^2-$(H)_2$ dimers, trimers, or even higher oligomers composed of **VA** units (Scheme 2.4).[18] Similar oligomerizations of isoelectronic intermediates were reported to be formed from Crabtree's [Ir(diene)(PCy_3)(pyridine)][PF_6] catalysts in the presence of H_2[22] or the [$Re(H)_7(PPh_3)_2$] complex at elevated temperatures.[23]

2.2.3. Preparation of [Re(*o*C_{PPh}-P∩P)(η^2-ethylene)Br(NO)] (VII)

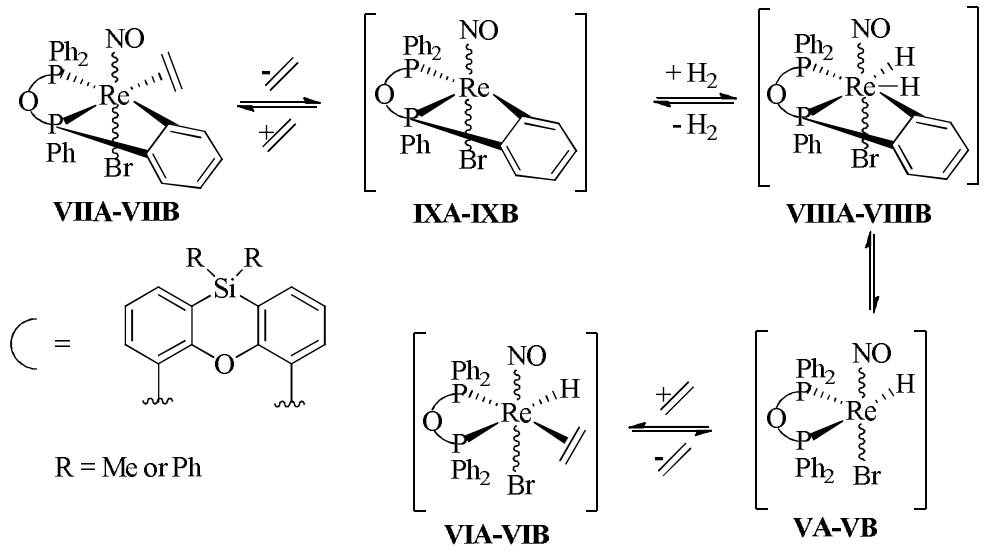
Then, we thought to carry out the reaction of **IIA** or **IIIA** with excess of Et_3SiH in the presence of ethylene as an additional auxiliary. Ethylene was considered an ideal ligand for the stabilization of the 16e species **V** because of its small size and appropriate binding capabilities to electron-rich Re(I) centers.[24] Additionally, in view of the application of the expected [Re)(P∩P)BrH(η^2-ethylene)(NO)] (**VI**) (Scheme 2.6) compound to function as a precatalyst in hydrogenation catalyzes, the ethylene ligand was anticipated to be initially hydrogenated to ethane, generating the desired highly reactive intermediate **V**, which could then drive the catalytic cycle.

The reaction of analogous complexes of the type **II** or **III** bearing diphosphine ligands proceeded smoothly in presence of an excess of Et_3SiH and 2 bar of ethylene to yield the isolable [Re(P∩P)BrH(η^2-ethylene)(NO)] (**IV**) complexes.[18] However, this reaction using complexes **IIA** or **IIIA** of mixture of both and **IIB** or **IIIB** or a mixture of both unexpectedly



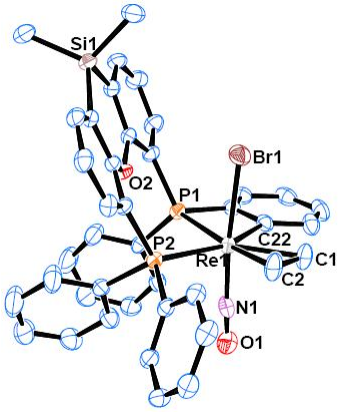
Scheme 2.5. Reaction of **IIA** and **IIB** with Et_3SiH and ethylene to from the ortho metallated rhenacycles **VIIA** and **VIIB** respectively.

furnished two ortho metalated isomers in either case [Re(*o*C_{PPh}-**A**)(η^2-ethylene)Br(NO)] (**VIIA1** and **VIIA2)** in a ration of 1:0.4 as well as [Re(*o*C_{PPh}-**B**)(η^2-ethylene)Br (NO)] (**VIIB1** and **VIIB2)** in a ration of 1:0.3 respectively, which were isolated by column chromatography under normal conditions (Scheme 2.5). Single crystals of all these compounds could be obtained suitable for their structural characterization by X-ray diffraction (Figure 2.4). All these isomers were found to be stable in both solution and solid state. We propose the ortho metalation to proceed via the unsaturated 16e species [Re(**A**)BrH(NO)] (**VA**). This species bearing a comparatively large bite angle diphosphine can apparently not sufficiently be stabilized by the binding of ethylene or CH_3CN. These

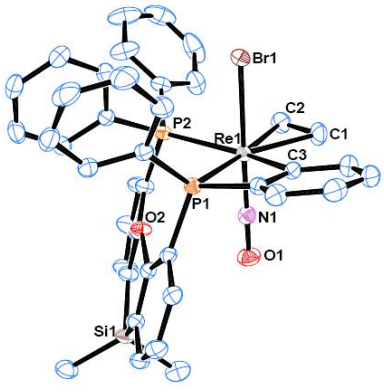


Scheme 2.6. Transformation of **IVA** and **IVB** into **IVA** and **IVB**.

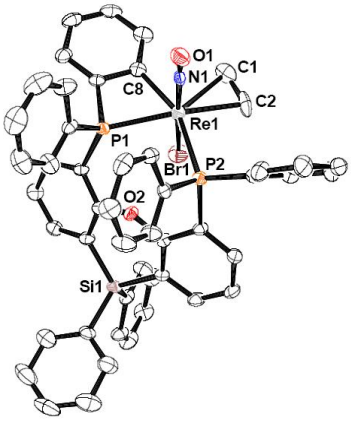
auxiliary ligands can dissociate and the remaining unsaturated species are reactive enough to activate the *o*C-H bond of one Sixanphos phenyl units forming the [Re(oC$_{PPh}$-P∩P)Br(H_2)(NO)] (**VIIIA** and **VIIIB**) species, which in turn can undergo a H_2/ethylene ligand exchange forming, via the [Re(oC$_{PPh}$-P∩P)Br(NO)] complexes (**IXA** and **IXB**), **VIIA** and **VIIB** isomers, respectively (Scheme 2.6).



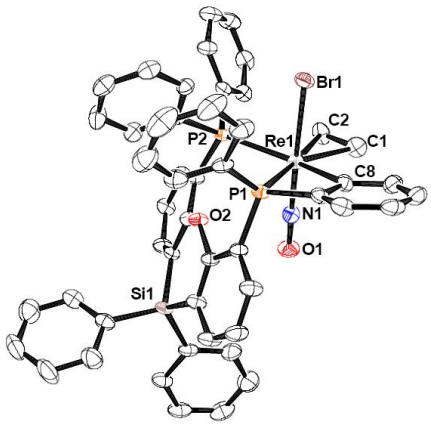
VIIA1; Selected bond distances: C1Re1: 2.194(3), C2Re1: 2.225(3), C22Re1: 2.165(3), N1Re1: 1.819(3), P1Re1: 2.5039(8), P2Re1: 2.5605(8), Br1Re1: 2.5816(3); Selected bong angles: P1Re1P2: 94.41(2), C1Re1C2: 36.9(1), N1Re1Br1: 174.44(9), P1Re1Br1: 87.18(2), P2Re1Br1: 91.70(2), C22ReP1: 64.61(8).



VIIA2; Selected bond distances: C1Re1: 2.199(2), C2Re1: 2.235(2), C3Re1: 2.177(2), N1Re1: 1.747(2), P1Re1: 2.5017(6), P2Re1: 2.5741(5), Br1Re1: 2.5912(2); Selected bong angles: P1Re1P2: 91.73(2), C1Re1C2: 37.11(8), N1Re1Br1: 179.01(6), P1Re1Br1: 90.84(1), P2Re1Br1: 85.99(1), C3ReP1: 64.67(6).



VIIB1; Selected bond distances: C1Re1: 2.228(8), C2Re1: 2.219(6), C8Re1: 2.170(5), N1Re1: 1.842(4), P1Re1: 2.487(1), P2Re1: 2.576(2), Br1Re1: 2.5767(6); Selected bong angles: P1Re1P2: 93.19(4), C1Re1C2: 33.7(2), N1Re1Br1: 176.2(1), P1Re1Br1: 92.33(3), P2Re1Br1: 92.33(3), C8ReP1: 64.6(1).



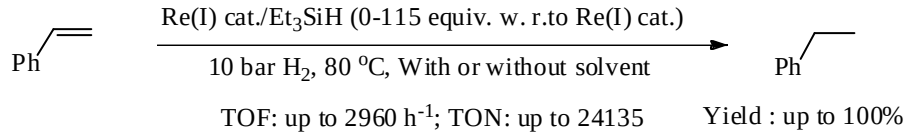
VIIB2; Selected bond distances: C1Re1: 2.183(8), C2Re1: 2.238(6), C8Re1: 2.174(5), N1Re1: 1.758(4), P1Re1: 2.485(1), P2Re1: 2.546(1), Br1Re1: 2.589(1); Selected bong angles: P1Re1P2: 92.91(4), C1Re1C2: 37.0(2), N1Re1Br1: 178.3(2), P1Re1Br1: 91.26(3), P2Re1Br1: 85.82(3), C8ReP1: 64.5(1).

Figure 2.4. Molecular structure of **VIIA1**, **VIIA2**, **VIIB1** and **VIIB2**. Anisotropic displacement parameters are depicted at the 50% probability level. Hydrogen atoms and solvent molecules are omitted for clarity.

2.2.4. Hydrogenation of Olefins Using the Complexes of the Type VII

Complexes **VIIA** and **VIIB** turned out to be (pre)catalysts for the hydrogenation of olefins showing activities comparable to Wilkinson or Osborn-type Rh catalysts.[25,10a] To explore the catalytic capabilities **VIIA** and **VIIB** in the catalytic hydrogenations of olefins, we employed a press gas flow controller for quantitative kinetic monitoring. Hydrogenation of styrene under the addition of various co-catalysts and a screening of solvents under a H_2 pressure of 10 bar at 80 °C is shown in Table 2.1. The reaction rates were found to be drastically improved when the reactions were carried out in a suitable solvent. Slower reaction led to the polymerization of styrene. Toluene was found to be an ideal choice among the tested solvents. Also, addition of Et_3SiH as a co-catalyst was found not only to increase the rate of reaction, but also to stabilize the species in order not to decrease the activity until the substrate was fully consumed. The catalytic performance of the two isomers, **VIIA1** and

Table 2.1. Hydrogenation of styrene using catalyst X under 10 bar H_2 at 80 °C.[a]



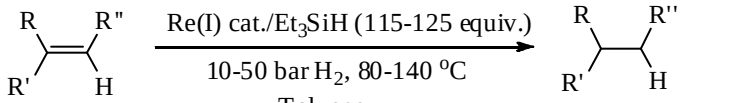
Entry	Catalyst	Solvent	Et_3SiH (Equiv.)[b]	TOF (h^{-1}) (1^{st} h)	TOF (h^{-1}) Overall	Time (h)	TON	Conversion (%)
1	**VIIA1**	-	-	929	148	29	4308	18
2	**VIIA2**	-	-	1157	197	29	5703	24
					155	86	13324	55
3	**VIIA2**	Toluene	-	2207	428	15	6418	27
4	**VIIA1**	Toluene	115	2414	2414	10	24135	100
5	**VIIA2**	Toluene	115	2961	2961	8	24135	100
6	**VIIA2**	Neat	115	1518	1518	16	24135	100
7	**VIIA2**	Toluene	575	1707	1707	14	24135	100
8	**VIIA2**	Toluene	23	2379	2379	10	24135	100
9	**VIIA2**	THF	115	2601	1006	24	24135	100
10	**VIIA2**	DCM	115	2242	2194	11	24135	100

[a]5 mg of catalyst was used with 15 mL of styrene and 10 mL of solvent, carried out using a Büchi pressgas flow controller and monitor. [b]With respect to catalyst.

VIIA2, in hydrogenations was found to be somewhat different on a quantitative scale, pointing to the fact that under catalytic conditions a **1** ↔ **2** isomerization[14] does not take place. In absolute numbers, however, these differences appeared to be small (Table 2.1). TOFs of up to 2960 and TONs of more than 24000 could be realized under these relatively mild conditions in the hydrogenation of styrene.

Then, we applied this hydrogenation strategy for a variety of substrates including the sterically demanding disubstituted substrates cyclohexene, α-methylstyrene, and dimethyl itaconate using catalysts **VIIA1** and **VIIIA2** along with Et_3SiH as a co-catalyst in toluene (Table 2.2). Using **VIIA**, an alkyne, like phenyl acetylene could also be hydrogenated completely to ethyl benzene, however, phenyl acetylene was found to be relatively strongly

Table 2.2. Hydrogenation of various olefins and phenylacetylene using catalyst **VII**.[a]



TOF: up to 14000 h^{-1}

R, R', R'' = alkyl, aryl, C(O)OMe, $CH_2C(O))Me$ TON: up to 31500

Entry	Olefin	Cat.	Temp.	TOF (h^{-1})		Time (h)	TON	Conv. (%)
				(1^{st} h)	Overall			
1	1-Hexene	**VIIA1**	80	4867	3139	2	6278	28
2	1-Hexene	**VIIA1**	120	4145	7796	0.5	3898	17
					-	2	4405	20
3	1-Hexene	**VIIA2**	60	2818	2834	2.5	7086	32
4	1-Hexene	**VIIA2**	80	4120	3375	1.5	5063	23
5	1-Hexene	**VIIA2**	120	3644	6126	0.5	3063	14
					2601	1.5	3902	18
6	Cyclohexene	**VIIA1**	120	601	372	17	6327	23
7	Cyclohexene	**VIIA2**	120	1231	566	18	10190	37
8	Styrene	**VIIA1**	120	6996	6996	3.75	24135	100
9	Styrene	**VIIA2**	120	8048	8048	3	24135	100
10	Styrene	**VIIA**	120	7485	7485	3.25	24135	100
11	Styrene	**VIIB**	120	8200	8200	3	27402	100
12	α-Methylstyrene	**VIIA1**	120	1820	1820	11	20025	100
13	α-Methylstyrene	**VIIA2**	120	1940	1940	10.3	20025	100
14[b]	Dimethyl itaconate	**VIIA1**	140	4038	595	41	24400	73
15	Dimethyl itaconate	**VIIA2**	140	4915	500	63	31492	95
16[b]	Phenylacetylene	**VIIA**	140	-	232[c]	10	2322	100
17[b]	Phenylacetylene	**VIIA**	140	1774/ 1067[d]	-	36	5239/ 2695[d]	12.5/ 6.4[d]

[a]Unless mentioned, 5 mg of catalyst, 0.1 mL of Et_3SiH and 2/3(substrate in mL) mL of toluene under 10 bar of H_2 applied using a Büchi pressgas flow controller and monitor. [b]50 bar of H_2, yields and conversions by GC/MS based on the consumption of the substrate. [c]3.6 mg of catalyst and 1 mL of phenylacetylene (0.043 mol%). [d]Ratio between styrene and ethylbenzene.

coordinating to the rhenium centre, which made the styrene to undergo hydrogenation comparatively in a much slower rate, until the whole alkyne was consumed.

2.2.5. Kinetics and Mechanism of the Hydrogenations Using Complexes of the Type VII

However, **VIIA** and **VIIB** were not efficient in hydrogenation of 1-hexene in comparison to that of styrene. Concomitant to the hydrogenation process, an intervening isomerization reaction, transforming 1-hexene into Z/E-2-hexene, which was found to proceed at a rate comparable to that of hydrogenations under catalytic conditions (80 °C, 10 bar H_2), and these internal olefins are hydrogenated at a much slower pace.

The reaction rates were found to be zeroth order in olefin concentration. This implies relatively strong olefin binding and a high olefin affinity to the rhenium center, which leads already at very low olefin concentration to quantitative olefin saturation of the catalyst. Probing of the kinetic isotope effect (KIE) with H_2 and D_2 revealed a kH_2/kD_2 value of 0.46 which suggest a late transition state of reductive elimination process as the rate limiting step (Table 2.3, entries 13 and 14). When complex **VIIA** was reacted with 2 bar of D_2 at 90 °C in benzene, we observed apart from ethane analyzed by ^{1}H NMR spectroscopy, the incorporation of D in the *ortho* carbon atom of the phenyl group (7.15 ppm) on P atom as well as Re-D species (-2.62 ppm) as analyzed by ^{2}H NMR spectroscopy (Scheme 2.7). Storage of this sample for a week led to the formation of single crystals suitable for X-ray diffraction studies which revealed the dinuclear H (D) bridged complex **XA** (Figure 2.5).

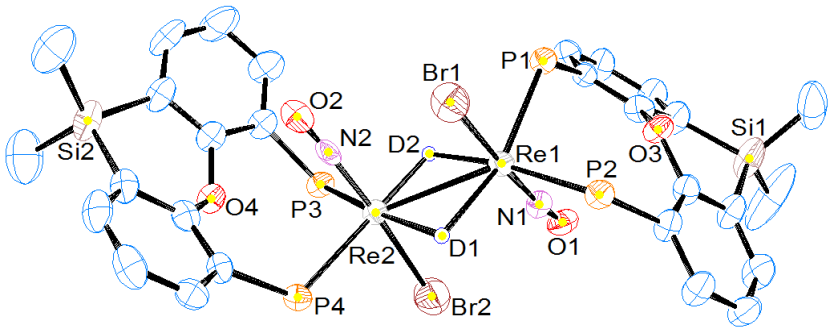
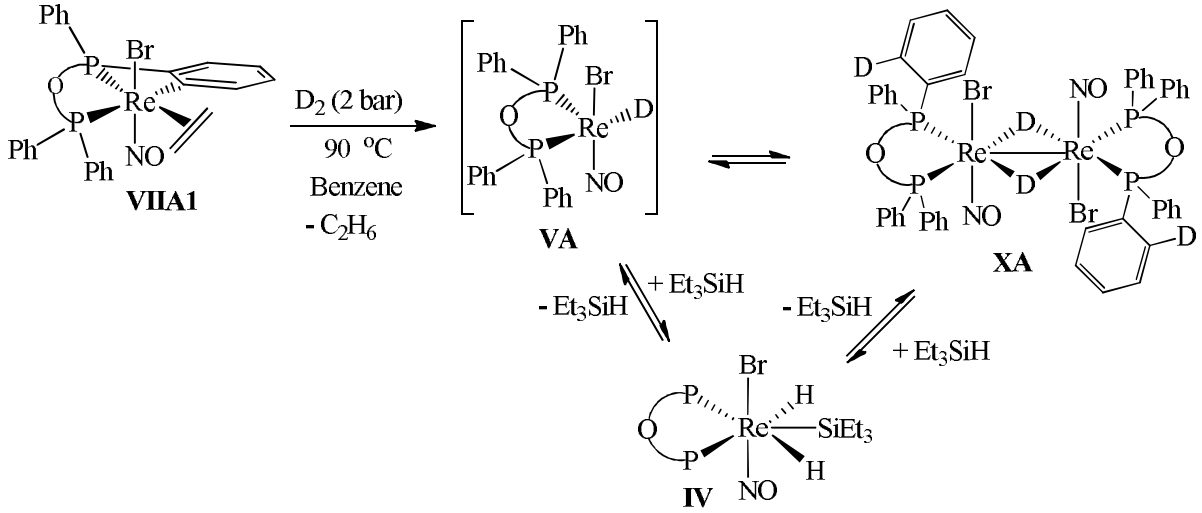
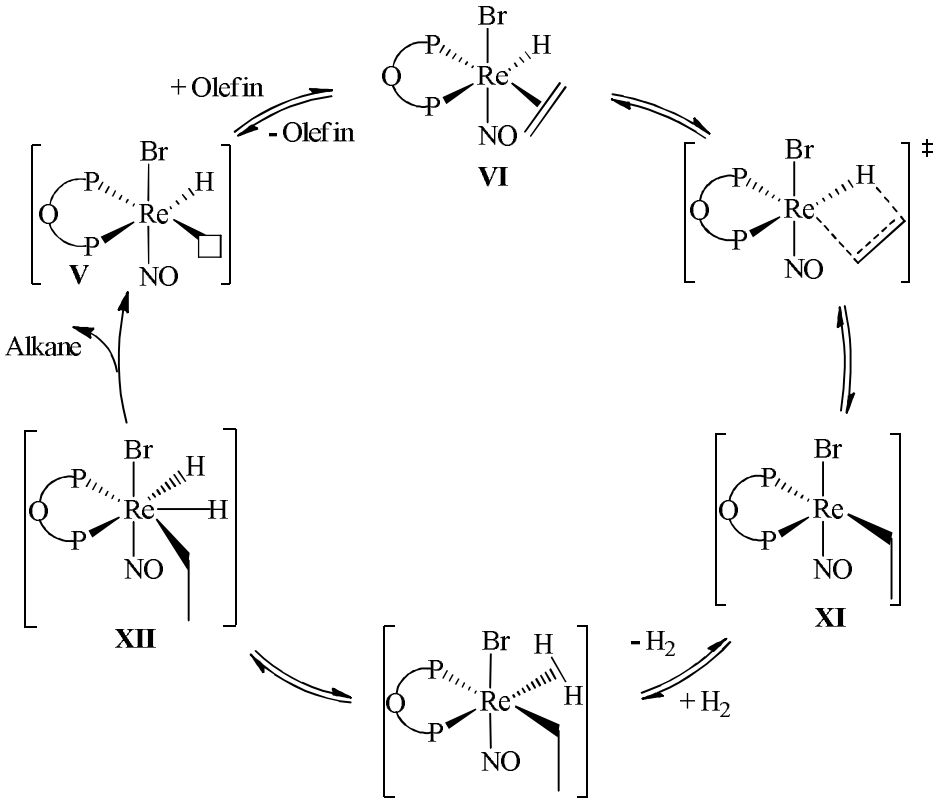


Figure 2.5. Molecular structure of complex **XA**. Anisotropic displacement parameters are depicted at the 50% probability level. Hydrogen atoms, phenyl groups on P atoms and solvent molecules are omitted for clarity.

This indicated that the complex **VII** underwent hydrogenolysis of the Re-C bond to form subsequently the species **VI**. Insertion of ethylene into the Re-H bond is supposed to give rise to the coordinatively unsaturated 16e ethyl species **XI**. Dihydrogen coordination and



Scheme 2.7. Reaction of **VIIA1** with D_2.



Scheme 2.8. Proposed catalytic cycle for the hydrogenation of olefins using **VII**.

oxidative addition to this complex is followed by reductive elimination of the alkane, would regenerates the coordinatively unsaturated 16e complex **V** which has also be considered as the active species of the catalytic reaction course (Scheme 2.8). This species, would dimerize in the absence of ethylene to give the stable 18e **XA**. In the presence of olefin, **V** would form the species **VI**, which is capable of undergoing ortho metallation reaction to form the rhenacycles. Now, the crucial role of Et_3SiH as a co-catalyst is presumed to lie in the cleavage of the dinuclear complex **X** forming the active species **V**, via the silyldihydridorhenium species **IV** (Scheme 2.7).

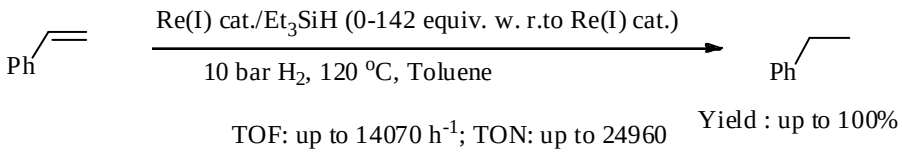
The observed inverse kinetic isotopic effect indicated a late transition state as rate limiting. This could be attributed to either the reductive elimination of the alkane from species **XII** or that of the phenyl group from the ortho metallated dihydride species **VIII**, both to form the active species **V** (Scheme 2.8). However, the former step as rate limiting can be ruled out when the same active species formed in the hydrogenation reactions using complex **IIIA**, where the CH_3CN present in the catalyst would suppress the ortho metallation pathways, showed a normal DKIE in the hydrogenation of styrene (vide infra).

2.2.6. Hydrogenation of Olefins and their Mechanism Using Complexes of the Type II and IIIA

Then the strategy of hydrogenation reaction of styrene was tested using the complexes **IIB-IIC** and **IIIA** or a mixture of both **IIA** and **IIIA** (Table 2.3; for a comparison, various catalytic systems are also shown). It is worth mentioning that either **IIA**, **IIIA** or a mixture of both showed the same activity for hydrogenation and related reactions indicating that the same active species is formed and operative irrespective of the ratio of **II** and **III**. Since most of the reactions are carried out after a prolonged storage of these complexes leading **IIA** to form **IIIA**, we will be using the notation of **IIIA** for the reactions hereafter. All these

complexes in the absence of a co-catalyst were found to be active catalysts for these hydrogenation reactions, but were comparatively slow leading to partial polymerization of

Table 2.3. Hydrogenation of styrene using various catalysts under 10 bar H_2 at 120 °C.[a]



Entry	Catalyst	Co-catalyst[b]	TOF (h^{-1})	TON	Conversion (%)
1	**IIIA**	-	150	750	-[c,d]
2	**IIIA**	-	1063	2126	-[c,e,]
3	**IIIA**	-	1700	1700	85[f]
4	**IIIA**	Et_3SiH	14073	26629	100
5	**IIB**	Et_3SiH	11701	29896	100
6	**VII**	Et_3SiH	7540	23096	100
7	**VIIA**	Et_3SiH + CH_3CN	10916	24135	100[g]
8	**VIIA**	Et_3N	9249	24135	100
9	**VIIA**	Et_3SiH	16414	24135	100
10	**IIIA**	Et_3SiH	9490	26629	100
11	**XIIIA**	Et_3SiH	8590[h]	28957	100[i]
12	**XIVD**	Et_3SiH	2710[c]	21181	100[i]
13	**IIIA**	Et_3SiH	9490	26629	100[j]
14	**VIIA**	Et_3SiH	16414	25135	100[j]

[a]Unless mentioned, 5 mg of catalyst was used with 15 mL of styrene (0.00472-0.00335 mol%). [b]10 mL of solvent, carried out using a Büchi press gas flow controller and monitor. [b]0.1 mL of Et3SiH (115-126 equiv. with respect to catalyst). [c]Partially polymerized. [d]Run for 5 h. [e]30 bar H_2 and run for 2 h. [f]0.05 mol% of catalyst under 50 bar H_2 at 90 °C run for 1 h. [g]10 equiv. of CH_3CN with respect to catalyst was added. [h]Untill 60% conversion; decrease in activity was observed after this leading to completion of the reaction in 15 h. [i]For the first 1 h; decrease in activity was observed from the beginning itself leading to completion of the reaction in 19 h. [j]Reaction with 10 bar of D_2.

styrene, unless higher catalyst loadings were adopted, when compared to reactions applying the addition of Et_3SiH as an activating co-catalyst (Table 2.3, entries 1-3). The mechanism which is thought to be operative in the hydrogenation using **IIIA** as potent catalysts in the absence of a co-catalyst will be discussed in Chapter 4.

However, the active species in the catalytic hydrogenation reactions using **IIIA**, **IIB-IIC** with Et_3SiH as co-catalyst is undoubtedly species **V**, since all the components included in the reaction of formation of **VII** and their catalytic hydrogenations are present here. In addition, one has to take into consideration the availability of stoichiometric quantities of CH_3CN and Et_3SiBr. Surprisingly, these reactions were found to be much more active in the hydrogenation of styrene. Also, a small DKIE value of 1.47 was observed replacing H_2 by D_2. Addition of 10 equiv. of CH_3CN in the hydrogenation system consisting of **VII** was found to increase the rate of the reaction. Even the addition of a 10 equiv. of triethylamine with respect to **VIIA** was found to increase the rate of reaction. This amine was added assuming that the CH_3CN, which is part of the complexes **III** would undergo hydrogenation to form this substituted amine. The ability of this complex to hydrogenate nitriles was found under forcing conditions giving higher substituted amines (Chapter 3), which would stabilize the active species **V**.

From all these observations, one can conclude that the presence of stoichiometric amounts of CH_3CN in the reaction medium would stabilize the active species forming a resting state so that the latter would not undergo oxidative addition reactions leading to ortho metallation, where the reverse, reductive elimination of a phenyl group expected to be slow and the rate limiting. Thus, a catalytic cycle without the ortho metallation steps, would operate for the hydrogenation reactions using **III**. Homolytic splitting of H_2 by oxidative addition is expected to be rate limiting here.

A comparison of the activity of all these catalysts **IIIA**, **IIB** and **IIC** as well as **VIIA**, **VIIB** and **VIIA**+CH_3CN systems, all along with Et_3SiH as a co-catalyst carried out under 10 bar of H_2 pressure at a temperature of 120 °C in toluene as a solvent are shown as kinetic plot with monitoring of the H_2 consumption in Figure 2.6.

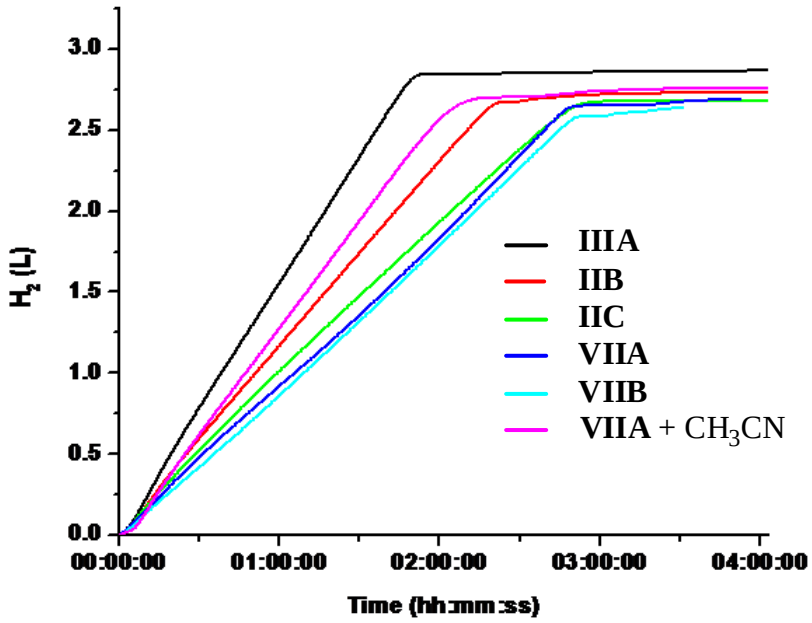
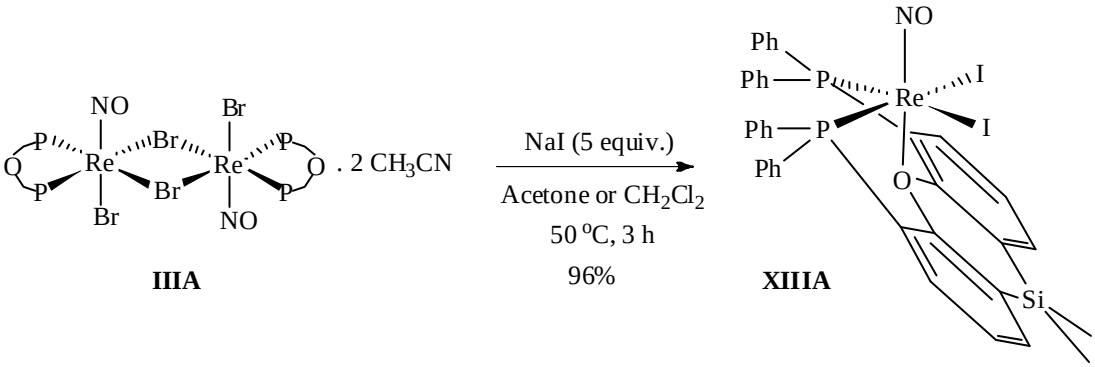


Figure 2.6. Comparison of the H_2 consumption of various catalyses for hydrogenation of styrene under constant H_2 pressure of 10 bar at 120 °C in toluene.

2.2.7. Preparation of [Re(POP)I_2(NO)] (POP = A) and Catalytic Hydrogenation of Styrene

Then, we thought to prepare the diiodo complex analogous to **IIA** of **IIIA** to study the effect of the halide influence in these catalyses. We reacted **IIIA** with NaI in acetone or dichlorometane at a temperature of 50 °C (Scheme 2.9). The ^{31}P NMR spectrum of the isolated compound showed a new singlet resonance at 24.2 ppm, but the ^{1}H NMR spectrum did not show any CH_3CN signal. Single crystals suitable for X-ray diffraction were obtained when benzene was layered over a dichloromethane solution of this compound, which was

structurally analyzed to be the diiodo complex **XIIIA,** where the Sixantphos ligand of this compound was found coordinated in a tridentate fashion with the O atom also involved in the



Scheme 2.9. Reaction of **IIIA** with NaI.

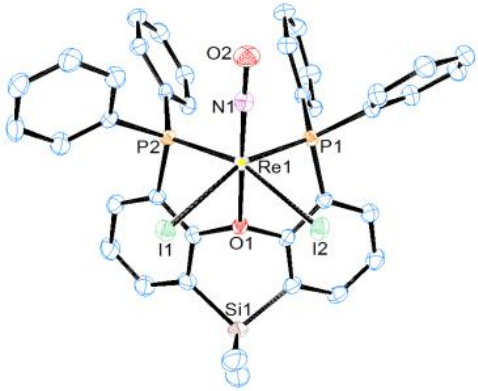


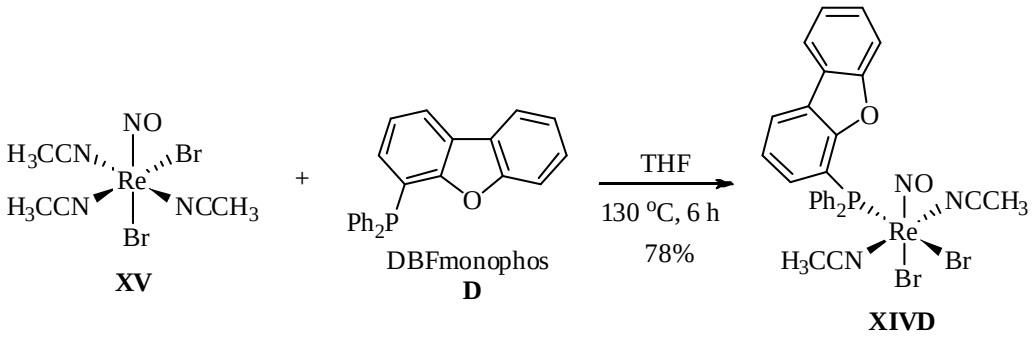
Figure 2.7. Molecular structure of complex **XIIIA** Anisotropic displacement parameters are depicted at the 50% probability level. Hydrogen atoms and solvent molecules are omitted for clarity. Selected bond lengths: Re1-I1: 2.7952(2), Re1-I2: 2.7976(2), Re1-O1: 2.221(2).

bonding to the rhenium centre *trans* to the NO ligand and the two iodides were found disposed *trans* to the diphosphine ligand (Figure 2.**7**).

The hydrogenation reaction of styrene using this complex **XIIIA** was found to be inferior in activity when compared to that of **IIIA**. However, the strategy to add Et_3SiH as a co-catalyst was found to drastically increase the efficiency of this reaction, but still was inferior to the reaction using **IIIA** under the same conditions otherwise (Table 2.3, entry 11).

2.2.8. Preparation of [Re(DBFmonophos)(CH_3CN)$_2$$Br_2$(NO)] (XIVD) and Catalytic Hydrogenation of Styrene

As described in Chapter 4, the complexes **IIIA** and **XIIIA** were found to be highly active for the hydrogenation of imines, and as a step on the elucidation of their catalytic reaction courses, we later prepared the monophosphine complex [Re(**D**)(CH_3CN)$_2$$Br_2$(NO)]



Scheme 2.10. Preparation of [Re(DBFmonophos)(CH_3CN)$_2$$Br_2$(NO)].

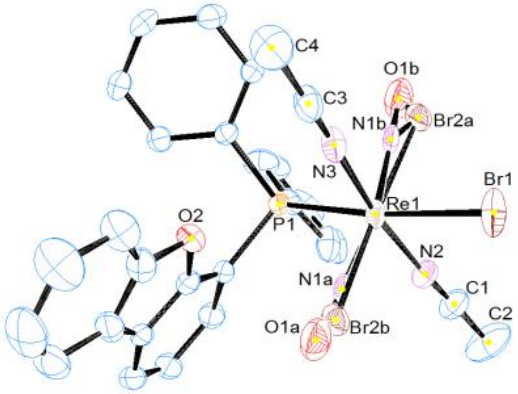


Figure 2.8. Molecular structure of complex **XIVD** Anisotropic displacement parameters are depicted at the 50% probability level. Hydrogen atoms and solvent molecules are omitted for clarity. Selected bnd lengths: Re1P1: 2.40005(8), Re1Br1: 2.6037(4), Re1N2: 2.070(3); Re1N3: 2.068(3).

(**XIVD)** bearing the ligand DBFmonophos (**D**)[26] by the reaction of *mer*-[Re(CH_3CN)$_3$ Br_2(NO)] (**XV**)[27] with **D** in THF (Scheme 2.10). Single crystals suitable for X-ray diffraction analysis was obtained when pentane was layered on a dichloromethane solution of this

compound allowing it to be characterized structurally by single crystal X-ray diffraction (Figure 2.8).

Surprisingly, though far less efficient as catalyst when compared to the diphosphines discussed, this monophosphine rhenium complex **XIVD** was also found to be active in the hydrogenation of styrene along with Et_3SiH as a co-catalyst (Table 2.3, entry 12).

2.3. Conclusion

Large bite angle diphosphine nitrosyl rhenium(I) complexes of the type [Re(P∩P)(CH_3CN)Br_2(NO)] (**II**) and [Re_2(**A**)$_2$$(Br)_2$(μ-Br)$_2$$(NO)_2$].2$CH_3CN$ (**IIIA**) could be prepared. On attempts to prepare complexes of the type [Re(P∩P)(η^2-ethylene)HBr(NO)] (**VI**), where the H and ethylene *cis* to each other, an unusual reactivity driven them to ortho metallation of one of the phenyl groups of the diphosphine ligand. This led to the formation of four membered rhenacycles of the type [Re($o$$C_{PPh}$-P∩P)($\eta^2$-ethylene)Br(NO)] (**VII**). These complexes when reacted with H_2 underwent hydrogenolysis of the Re-C_{Ph} bond leading to the transient formation of the desired complexes which were highly reactive to hydrogenate the olefins generating the active species [Re(P∩P)HBr(NO)] (**V**). All the complexes **II, III** and **VII** were found to be active catalysts for the hydrogenation of olefins, for instance, TOFs of up to 14000 h^{-1} could be achieved under a H_2 pressure of 10 bar at 120 °C, without the loss of activity, and that too with a relatively high quantity of 15 mL of styrene giving rise to complete conversion to ethyl benzene. A catalytic cycle operating for these hydrogenation reactions using **VII** and **II**, the latter in the presence of Et_3SiH as co-catayst is elucidated. The activity could be drastically improved by the addition of Et_3SiH as co-catalyst in reactions using **VII**. Oxidative addition by heterolytic splitting of H_2 is assumed to be the rate limiting step for hydrogenation reactions using complexes **II** and **IIIA.** However, the reductive elimination from the ortho metallated species **VIII** is proposed to be the rate limiting step in

the hydrogenation reactions using **VII**. The mechanism of the hydrogenation reactions using **II** or **III** in the absence of any co-catalyst will be discussed in Chapter 4.

2.4. Experimental Section

General Procedures

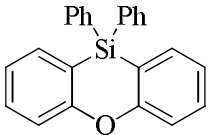
All manipulations were carried out under an atmosphere of dry nitrogen using standard Schlenk techniques or in a glove box (M. Braun 150B-G-II) filled with dry nitrogen. Solvents were freshly distilled under N_2 by employing standard procedures and were degassed by pump freeze-thaw cycles prior to use. $[ReBr_5(NO)][NEt_4]_2$ (**I**)[17], Sixantphos (**A**)[16b], and Thixantphos (**C**)[16] were prepared according to reported procedures. Triethylsilane was purchased from abcr speciality chemicals and used without further purification.

^{1}H NMR, ^{13}C{^{1}H} NMR and ^{31}P{^{1}H} NMR data were recorded on a Bruker-500 MHz spectrometer. Chemical shifts are expressed in parts per million (ppm) referenced to the deuterated solvent used. All chemical shifts for the ^{31}P{^{1}H} data are reported downfield in ppm relative to external 85% H_3PO_4 at 0.0 ppm. Signal patterns are reported as follows: s, singlet; d, doublet; t, triplet; td, doublet of triplet; dt, triplet of doublet, m, multiplet. IR spectra were obtained by using ATR methods with a Bio-Rad FTS-45 FTIR spectrometer. Signal intensities in the spectra are reported as follows: s, strong; m, medium; w, weak. Elemental microanalysis was carried out with Leco CHNS-932 analyser.

Preparation of Sixantphos-PPh_2 (B)

An analogues procedure for the synthesis of sixantphos (**A**) was adopted[16a].

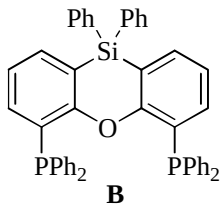
10,10-Diphenylphenoxasilin



At room temperature a solution of diphenyl ether (1.0 g, 5.88 mmol) in THF (5 mL) was added dropwise to a mixture of 2.5 M *n*-butyllithium in hexanes (5.2 mL, 13.0 mmol) and TMEDA (2.1 mL, 13.0 mmol). When the phenyl ether addition was complete, the reaction mixture was stirred for 16 h. The reaction mass was diluted with ether (5 mL) and to this a solution of dichlorodiphenylsilane (1.22 mL, 5.88 mmol) in ether (10 mL) was added over 40 minutes and the mass was stirred for another 16 h and then water (10 mL) was added. The mixture was stirred for 2 h. The organic layer was separated and the aqueous layer was extracted with ether (15 mL). The combined organic layers were washed with 10 mL of water. The combined organic layers were dried

over $MgSO_4$. The solvent was removed on a rotary evaporaor. The semisolid oil was crystallized form 2-propanol, resulting in white crystals. Yield: 0.55 g (55%); IR (KBr, cm^{-1}): 3064 (w), 3048 (w), 3006 (w), 1956 (w), 1816 (w), 1618 (m), 1588 (s), 1570 (s), 1481 (w), 1460 (s), 1420 (s), 1429 (s), 1300 (s), 1266 (s), 1216 (s), 1183 (m), 1156 (m), 1126 (s), 1110 (s), 1075 (m), 1026 (m), 997 (m), 885 (m); 1H NMR (500 MHz, CDCl3): δ 7.19 (td, 2H, *J* = 12, 1.5 Hz), 7.29 (d, 2H, *J* = 13 Hz), 7.40-7.43 (m, 4H), 7.45-7.49 (m, 2H), 7.50-7.53 (m, 2H), 7.62-7.66 (m, *J* = 6H); 13C NMR (125 MHz, $CDCl_3$): 116, 118.3, 122.8, 128.1, 130.0, 131.7, 134.0, 135.4, 135.9, 160.4.

4,6-Bis(diphenylphosphino)-10,10-diphenylphenoxasilin (Sixantphos-Ph_2) (B)



B

At room temperature 1.4 M sec-butyllithium in 98/2 cyclohexane/hexane (7.2 mL, 8.55mmol) was added dropwise to a stirred solution of 10,10-Diphenylphenoxasilin (1 g, 2.85 mmol) and TMEDA (1. 3 mL, 8.55 mmol) in dry ether (40 mL). When all sec-butyllithium was added, the reaction mixture was stirred for 16 h. Then a solution of chlorodiphenylphosphine (1.6 mL, 8.55 mmol) in hexane (15 mL) was added, and the reaction mixture was stirred for another 16 h. The solvent was removed in *vacuo***.** The resulting solid oil was dissolved in dichloromethane (20 mL), washed with water (2 × 10 mL) and dried over $MgSO_4$ and the solvent removed on a rotary evaporator. The resulting oil was washed with hexanes and crystallized from 1-propanol to get the title compound as white powder. Yield: 1.17 g (57%); IR (KBr, cm^{-1}): 3067 (w), 3051 (w), 3025 (w), 1956 (w), 1889 (w), 1825 (w), 1618 (w), 1578 (m), 1570 (m), 1476 (m), 1432 (s), 1397 (s), 1368 (s), 1301 (w), 1283 (w), 1235 (s), 1200 (s), 1155 (w), 111 (m),m 1066 (w), 1026 (w), 997 (w), 885 (w); ^{1}H NMR (500 MHz, $CDCl_3$): δ 6.75 (dq, 2H, *J* = 7.5, 2.0 Hz), 6.90 (t, 2H, *J* = 7 Hz), 7.10-7.19 (m, 20 H), 7.31 (t, 4H, *J* = 7.5 Hz), 7.36 (d, 2H, *J* = 7.5 Hz), 7.45 (dd, 2H, *J* = 7.5, 1.8 Hz), 7.52 (dd, 4H, *J* = 8, 1.5 Hz); ^{31}P {^{1}H} NMR (201 MHz, $CDCl_3$): δ -17.7 (s), ^{13}C NMR (125 MHz, $CDCl_3$): δ 116.4, 123.8, 128.7 (t, *J* = 3.4 Hz), 128.8, 130.6, 134.5, 134.7 (t, *J* = 10.6 Hz), 136.6, 136.7, 137.6, 138.6 (t, *J* = 6.6 Hz); Anal. (%). Calc for $C_{48}H_{36}OP_2Si$: C, 80.20; H, 5.05. Found: C, 79.98; H, 4.94.

Preparation of [Re(A)(CH_3CN)Br_2NO] (IIA), [Re(B)(CH_3CN)Br_2NO] (IIB) and [Re(C)(CH_3CN)Br_2NO] (IIC)

Compound IIA

$[ReBr_5(NO)]$ $[NEt_4]_2$ (**I**) (1 g, 1.14 mmol) and sixantphos (**A**) (0.85 g, 1.425 mmol) in acetonitrile (12 mL) was taken in an autoclave and heated to 200 ^oC for 4 h. Cooled to room temperature, filtered to get an yellow solid. It is washed with acetonitrile (2 × 4 mL) and dried to get 0.65 g, (56%) of the product **IIA**. Yellow solid; Yield: 56%; IR (KBr, cm^{-1}): 3046 (w), 2922 (w), 2360 (w), 1686 (s. *ν*(NO) belonging to **IIIA**), 1680 (s. *ν*(NO)), 1585 (w), 1379 (s), 1244 (m), 1211 (w), 1091 (w); ^1H NMR (500 MHz, $CDCl_3$): δ 0.52 (s, 3H), 0.62 (s, 3H), 2.19 (s, 3H), 6.65-7.85 (unresolved, 26 H); ^{31}P NMR (121 MHz, $CDCl_3$): δ -5.4 (br, s), -2.5 (br, s); Anal. (%). Calc for $C_{40}H_{35}Br_2N_2O_2P_2ReSi$: C, 47.48 %; H, 3.49; N, 2.77 %. Found: C, 47.21; H, 3.37; N, 2.94.

Compound IIIA

IR (KBr, cm^{-1}): 1686 (s. *ν*(NO); ^1H NMR (300 MHz, $CDCl_3$): δ 0.50 (s, 6H), 0.89 (s, 6H), 2.02 (s, 6H (lattice CH_3CN)), 6.65-6.80 (overlapping, 16H), 6.99 (t, 4h), 7.34-7.48 (overlapping 16H), 7.65-7.91 (overlapping, 16H) ^{31}P NMR (121 MHz, $CDCl_3$): δ 25.2 (s).

Re(**B**)$(CH_3CN)Br_2NO$ (**IIB**) and Re(**C**)$(CH_3CN)Br_2NO$ (**IIC**) were also prepared by this method, but with a different work up procedure for the latter. The reaction mass was filtered, washed with acetonitrile (2 x 2 mL). The combined acetonitrile layers were concentrated to dryness and extracted with THF (2 x 3 mL). This was concentrated to half of its volume and crystallized.

Compound IIB

Yellow solid; Yield: 52%; IR (KBr, cm^{-1}): 3045 (w), 2923 (w), 2362 (w), 1686, (s. *ν*(NO)), 1570 (w), 1435 (m), 1377 (s), 1241 (m), 1211 (w), 1091 (w); ^1H NMR (500 MHz, $CDCl_3$): δ 2.25 (s, 3H), 6.76-7.85 (unresolved, 36 H; $^{31}P\{1H\}$ NMR (121 MHz, $CDCl_3$): δ -4.8 (br, s), -2.0 (br, s), 25.4 (s, belonging to **IIIB**); Anal. (%). Calc for $C_{50}H_{39}Br_2N_2O_2P_2ReSi$: C, 52.87; H, 3.46; N, 2.47. Found: C, 52.55; H, 3.49; N, 2.21.

Compound IIC

Yellow solid; Yield: 47%; IR (KBr, cm^{-1}): 3052 (w), 2955 (w), 2362 (w), 1702, (s. *ν*(NO)), 1617 (w), 1482 (m), 1435 (s), 1400 (s), 1221 (w), 1211 (w), 1096 (m); ^1H NMR (300 MHz, $CDCl_3$): δ 2.09 (s, br, 3H), 6.45-7.85 (unresolved, 26 H); ^{31}P {1H} NMR (73 MHz, $CDCl_3$): δ 14.7--13.68 (s, br), 26.1 (s, belonging to **IIIC**); Anal.(%): Calc for $C_{38}H_{29}Br_2N_2O_2P_2ReS$: C, 46.30; H, 2.97; N, 2.84. Found: C, 45.99; H, 2.93; N, 2.65.

Preparation of [Re(*o*C_{PPh}-A)(*η2*-ethylene)Br(NO)] (VIIA) and [Re(*o*C_{PPh}-B)(*η2*-ethylene)Br(NO)] (VIIB)

Re(Sixantphos)$(CH_3CN)Br_2NO$ (**IIA**) (1 g, 0.99 mmol) was taken in dichloromethane (8 mL) and added triethylsilane (3 mL, excess) followed by ethylene gas at 2 bar. The solution is allowed to stir at 70 ^oC for 6 h.

Cooled to room temperature and the solvent was evaporated to dryness. The obtained solids were washed with toluene (2 × 2 mL) and dried to get the product as a mixture of diastereomers **IIA1** and **IIA2** in a ratio of 1 : 0.4 (0.634 g, 70%). The mixture is chromatographed on a silica gel column (Eluent: Hexane/Dichloromethane) to get the products **IIA1** (0.373 g, 41%) and **IIA2** (0.145 g, 16 %).

Compound VIIA1

Pale yellow solid; Yield: 41%; IR (KBr, cm^{-1}): 3046 (w), 2922 (w), 2360 (w), 1680 (s), 1585 (w), 1379 (s), 1244 (m), 1211 (w), 1091 (w); ^{1}H NMR (500 MHz, $CDCl_3$): δ 0.44 (s, 3H), 0.59 (s, 3H), 1.76 (q, 1H, *J* = 9.0 Hz), 2.72 (m, 1H), 3.13 (q, 2H, *J* = 9 Hz), 6.78 (td, 2H, *J* = 7.0, 1.5 Hz), 7.05 (td, 3H, *J* = 7.0, 1.5 Hz), 7.13-7.20 (m, 5H), 7.24-7.34 (m, 6H), 7.37-7.43 (m, 3H), 7.53 (t, 1H, *J* = 7.5, 1.5 Hz), 7.62 (d, 1H, 7.5 Hz), 7.68-7.72 (m, 2H), 7.82 (t, 1H, *J* = 7.5 Hz), 8.08 (quin, 1H, 4.0 Hz); ^{13}C {1H} NMR (125 MHz, $CDCl_3$): -2.8, 0.7, 49.3 (d, *J* = 6.3 Hz), 49.7 (d, *J* = 9.3 Hz), 117.4 (d, *J* = 50.0 Hz), 117.2 (d, 40.1 Hz), 121.2 (d, *J* = 2.2 Hz), 121.3 (d, *J* = 2.1 Hz), 123.6 (d, *J* = 6.3 Hz), 124.1 (d, *J* = 6.1 Hz), 124.3 (d, *J* = 6.1 Hz), 125.8 (d, *J* = 8.8 Hz), 127.9 (d, *J* = 3.2 Hz, 128.0 (d, *J* = 3.5 Hz), 128.7 (d, *J* = 10.5 Hz), 129.7 (d, *J* = 18.8 Hz), 129.8 (d, *J* = 2.9 Hz), 130.5 (d, *J* = 5.1 Hz), 131.7 (d, *J* = 38.7 Hz), 132.2 (d, *J* = 10.6 Hz), 132.4 (dd, *J* = 35.9, 2.8 Hz), 132.8 (t, *J* = 3.0 Hz), 133.4 (dd, *J* = 44.5, 2.7 Hz), 134.6 (d, *J* = 11.2 Hz), 135.6 (d, J = 10.7 Hz), 137.1 (d, *J* = 12.5 Hz), 149.1 (dd, *J* = 48.1 Hz, 6.2 Hz), 152.6 (dd, *J* = 60.0, 6.9 Hz), 161.8 (d, *J* = 5.0 Hz), 162.0 (d, *J* = 5.2 Hz). $^{31}P\{1H\}$ NMR (121 MHz, $CDCl_3$): δ -69.4 (d, *J* = 29.7 Hz), -12.7 (d, *J* = 29.7 Hz); Anal. (%). Calc for $C_{40}H_{35}BrNO_2P_2ReSi$: C, 52.34; H, 3.84; N, 1.53. Found: C, 52.68; H, 4.09; N, 1.53.

Compound VIIA2

Pale yellow solid; Yield: 16%; IR (KBr, cm^{-1}): 3045 (w), 2923 (w), 2362 (w), 1686 (s), 1570 (w), 1435 (m), 1377 (s), 1241 (m), 1211 (w), 1091 (w); ^{1}H NMR (500 MHz, $CDCl_3$): δ 0.51 (s, 3H), 0.54 (s, 3H), 1.99 (q, 1H, *J* = 8.0 Hz), 2.66 (m, 1H), 2.97-3.09 (m, 2H), 6.63 (td, 2H, *J* = 8.5, 2.5 Hz), 6.97 (tq, 1H, *J* = 8.5, 1.5 Hz), 7.12-7.31 (m, 7H), 7.32-7.37 (m, 3H), 7.38-7.42 (td, 2H, *J* = 7.5, 2.5 Hz), 7.48-7.54 (m, 3H), 7.60-7.65 (m, 3H), 7.68-7.72, (m, 2H), 7.83 (td, 1H, *J* = 8.0, 1.5 Hz), 8.05 (quin, 1H, *J* = 4.0 Hz); ^{13}C {1H} NMR (125 MHz, $CDCl_3$): -2.3, 0.6, 47.3 (d, *J* = 7.2 Hz), 48.4 (d, *J* = 10.0 Hz), 116.8 (d, *J* = 46.0 Hz), 117.2 (d, 37.4 Hz), 121.4 (d, *J* = 2.2 Hz), 121.5 (d, *J* = 2.1 Hz), 124.1 (d, *J* = 5.6 Hz), 124.6 (d, *J* = 5.6 Hz), 125.9 (d, *J* = 8.5 Hz), 127.6 (d, *J* = 9.6 Hz, 127.9 (d, *J* = 9.0 Hz), 128.5 (d, *J* = 10.5 Hz), 129.2 (d, *J* = 38.8 Hz), 129.8 (d, *J* = 2.9 Hz), 129.9 (d, *J* = 2.9 Hz), 130.0 (d, *J* = 4.1 Hz), 130.4 (d, *J* = 5.3 Hz), 130.8 (d, *J* = 18.5, 1.5 Hz), 132.7 (t, *J* = 3.0 Hz), 132.8 (dd, *J* = 41.2, 4.3 Hz), 133.3 (d, *J* = 9.3 Hz), 133.8 (d, *J* = 9.6 Hz), 134.1 (d, *J* = 2.8 Hz), 134.7 (d, *J* = 8.2

Hz), 134.8 (d, *J* = 2.5 Hz), 135.6, 136.9, 137.4, 151.2 (dd, *J* = 40.1 Hz, 5.0 Hz), 153.1 (dd, *J* = 54.2, 7.9 Hz), 161.0 (d, *J* = 5.6 Hz), 161.9 (d, J = 6.8 Hz). ^{31}P{1H} NMR (121 MHz, $CDCl_3$): -76.2 (d, *J* = 34 Hz), -22.8 (d, *J* = 29.3 Hz); Anal. (%). Calc for $C_{40}H_{35}BrNO_2P_2ReSi$: C, 52.34; H, 3.84; N, 1.53. Found: C, 52.71; H, 3.57; N, 1.51.

A similar procedure was adopted for the preparation of **[**Re(Sixantphos-Ph_2)(η^2-ethylene)Br(NO)] **(VIIB1 and VIIB2))** from compound **IIB**. Anal. (%). Calc for $C_{50}H_{40}BrNO_2P_2ReSi$ (1 : 0.3 mixture of diastereomers **VIIB1** and **VIIB2**): C, 57.58; H, 3.87; N, 1.34. Found: C, 57.35; H, 4.01; N, 1.23.

Compound VIIB1

Pale gray solid; Yield: 47%; IR (KBr, cm^{-1}): 3042 (w), 2989 (w), 2959 (w), 2916 (w), 2351(w), 1682 (s), 1573 (m), 1428 (m), 1408 (m), 1378 (s), 1261 (m), 1227 (m), 1206 (m), 1187 (m), 1103 (m), 1025 (m), 995 (m); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.84 (q, 1H, *J* = 8.5 Hz, 2.81 (q, 1H, *J* = 8.5 Hz), 3.19 (q, 2H, *J* = 8.5 Hz), 6.75 (t, 2H, *J* = 7.5 Hz), 7.03-7.13 (m, 3H), 7.15 (t, 2H, *J* = 1.5 Hz), 7.13-7.23 (m, 3H), 7.27-7.36 (m, 8H), 7.40-7.44 (m, 4H), 7.52 (d, 4H, *J* = 7.5 Hz), 7.54-7.57 (m, 2H), 7.67 (m, 2H), 7.74 (d, 2H, *J* = 7.0 Hz,), 7.78 (t, 1H, *J* = 8.0 Hz) 7.89 (t, 1H, *J* = 8.0 Hz), 8.13 (quin, 1H, *J* = 4.0 Hz); ^{31}P{1H} NMR ($CDCl_3$, 121 MHz): δ -68.8 (d, J = 30.2 Hz), -11.7 (d, J = 30.2 Hz).

Compound VIIB2

Pale gray solid; Yield: 15%; IR (KBr, cm^{-1}): 3045 (w), 2923 (w), 2362 (w), 1686 (s), 1570 (w), 1435 (m), 1377 (s), 1241 (m), 1211 (w), 1091 (w); ^{1}H NMR (500 MHz, $CDCl_3$): δ 2.07 (q, 1H, J = 8.5 Hz), 2.75 (m, 1H), 3.10 (m, 2H), (6.63 (t, 2H, *J* = 7.5 Hz), 6.98 (tq, 1H), 7.16-7.27 (m, 4H), 7.29-7.45 (m, 13H), 7.56 (m, 6H), 7.67-7.79 (m, 7 H), 7.90 (t, 1H, *J* = 8.0 Hz), 8.12 (quin, 1H, 4.0 Hz); ^{31}P{1H} NMR (121 MHz, $CDCl_3$): -75.5 (d, *J* = 30.2 Hz), -21.8 (d, *J* = 32.2 Hz).

Preparation of [Re(POP)$(I)_2$(NO)] (XIIIA)

Complex **IIIA** (0.1 g, 0.099 mmol) and NaI (0.074 g, 0.494 mmol) was taken in a 5 mL Schlenk flask. Acetone (1 mL) was added to it. The flask was closed and heated to 50 °C for 3 h. NaBr was observed to be precipitated out. The mixture was filtered, the solution was evaporated to dryness. It is extracted with dichloromethane (2 x 1 mL), evaporated and dried to get XIIIA as a yellowish brown solid (0.101 g, 0.0946 mmol, yield 96%). The same reaction was carried out in dichloromethane. The mixture after reaction was filtered, evaporated and dried to get **XIIIA** (0.1006 mg, yield 96%). IR (KBr, cm^{-1}): 3052 (w), 2922 (w), 1688 (s), 1586 (m), 1482 (m), 1434 (s), 1392 (m), 1368 (s), 1254 (w), 1158 (w), 1096 (m); ^{1}H NMR (500 MHz, $CDCl_3$): δ 0.50 (s, 3H), 0.78 (s, 3H), 6.66-6.72 (m, 8H), 6.95 (t, *J* = 6 Hz, 2H), 7.40-7.43 (m, 8H), 7.69 (d, *J* = 7 Hz, 2H), 7.84-7.89 (m, 6H);

$^{31}P\{1H\}$ NMR (121 MHz, $CDCl_3$): δ 24.4; Anal. (%). Calc for $C_{38}H_{32}I_2NO_2P_2ReSi$: C, 42.87; H, 3.03; N, 1.32. Found: C, 43.04; H, 3.16; N, 1.34.

$[Re(P)(CH_3CN)_2(Br)_2NO]$ (P = D, XVID)

$[Re(CH_3CN)_3(Br)_2NO]$[27] (**XV**) (0.1 g, 0.2 mmol) and DBFmonophos[26] (**D**) (0.074 g, 0.21 mmol) was taken in a glass autoclave and THF (1.5 mL) was was added to it. The vessel was closed and heated to 130 °C for 6 h. The yellow solids precipitated out were filrered. It is washed with THF (2 x 1 mL) and then with acetonitrile (1 mL). The solids were dried to get compound XIVD as a yellow solid (0.127 g, 0.156 mmol, yield 78%). IR (KBr, cm^{-1}): 3053 (w), 2970 (w), 2916 (w), 1703 (s), 1577 (m), 1482 (m), 1449 (s), 1435 (s), 1403 (s), 1367 (w), 1263 (w), 1187 (s), 1109 (w), 1093 (m), 1059 (m); ^1H NMR (500 MHz, $CDCl_3$): δ 2.42 (s, 3H), 2.46 (s, 3H), 7.27 (m, 1H); 7.33-7.43 (m, 10H), 7.76-7.82 (m, 4H), 7.97 (d, J = 7 Hz, 1H), 8.07 (d, J = 7 Hz, 1H), $^{31}P\{1H\}$ NMR (121 MHz, $CDCl_3$): δ 1.7 (s); Anal. (%). Calc for $C_{28}H_{23}Br_2N_3O_2PRe$: C, 41.49; H, 2.86; N, 5.18. Found: C, 41.49; H, 3.01; N, 5.05.

Typical Procedure for the Hydrogenation of Olefins

Catalyst IIIA (0.005 mg, 0.00494 mmol), Styrene (15 mL, 130.92 mmol) and Et_3SiH (0.091 mL, 0.57 mmol) were taken in a 50 mL stainless steel autoclave. Toluene (10 mL) was added to it. The vessel was closed and connected to a Büchi pressflow gas controller machine. The gas line was evacuated thrice and the line was charged with approx. 3 bar of H_2. The vessel was opened and it was evacuated carefully (thrice, not allowing pressure to go below 0 bar) to remove nitrogen. The vessel was charged with H_2 (10 bar) and the mass was immediately kept in an oil bath maintained at appropriate temperature. The consumption of the gas is measured from the graph, from which the conversion of styrene could be calculated (Figure 2.7).

For the hydrogenation of dimethyl itaconate and phenyl acetylene, the reaction vessel was charged with H_2 (50 bar) and kept in an oil bath maintained at 140 °C. In the case of dimethyl itaconate, the vessel was cooled to room temperature after 1 h, 15 h, 23 h, 36 h (and samplings were done) and in all thse cases, again H_2 (50 bar) was charged and kept in the oil bath. For both these substrates, the final reaction mass was analyzed by GC/MS (CP-3800 Saturn 2000MS/MS spectrometer, column: Agilent VF-5ms, 30m x 0.25mm x 0.25μm) and the yields were calculated on the basis of consumption of the substrates.

Compound: retention time (mass pesk); Dimethyl itaconate: 3.44 min (m/z: 173), dimethyl methylsuccinate: 3.21 min (m/z: 175); Phenylacetylene: 2.06 min (m/z: 102), styrene: 2.15 min (m/z : 204),

ethylbenzene: 2.02 min (m/z: 106).

2.5. References

1. a) J. G. de Vries, C. J. Elsevier, in *Handbook of Homogeneous Hydrogenation*; Eds.; Wiley-VCH: Weinheim, **2007**;
2. a) Zimmermann, S.; Sures, B. *Environ. Sci. Pollut. Res.* **2004**, *11*, 194-199; b) M. Schmid, S. Zimmermann, H. F. Krug, B. Sures, *Environ. Int*. **2007**, *33*, 385-390.
3. a) D. Heller, A. H. M. Vries, in *Handbook of Homogeneous Hydrogenation*, (Eds.: J. G. de Vries, C. J. Elsevier), Wiley-VCH: Weinheim, 2007; pp 1483-1516; b) Bartholomew, C. H. *Appl. Catal. A* **2001**, *212*, 17-60; c) Widegren, J. A.; Finke, R. G. *J. Mol. Catal. A* Chem. **2003**, *198*, 317-341.
4. a) D. M. Heinekey, M. H. Voges, D. M. Barnhart, *J. Am. Chem. Soc*. **1996**, *118*, 10792–10802; b) C. Bianchini, A. Marchi, L. Marvelli, *J. Am. Chem. Soc*. **2011**, *133*, 8168-8178; c) M. Peruzzini, A. Romerosa, R. Rossi, A. Vacca, *Organometallics* **1995**, *14*, 3203-3215; c) D. Gusev, A. Llamazares, G. Artus, H. Jacobsen, H. Berke, *Organometallics* **1999**, *18*, 75-89.
5. a) A. Choualeb, O. Blacque, H. W. Schmalle, T. Fox, T. Hiltebrand, H. Berke, *Eur. J. Inorg. Chem.* **2007**, 5246-5261; b) J. A. Gladysz, B. J. Boone, *Angew. Chem., Int. Ed. Engl*. **199**7, *36*, 550-583.
6. S. E. Clapham, A. Hadzovic, R. H. Morris, *Coord. Chem. Rev*. **2004**, *248*, 2201-2237.
7. A. Choualeb, E. Maccaroni, O. Blacque, H. W. Schmalle, H. Berke, *Organometallics* **2008**, 27, 3474-3481.
8. Y. Jiang, O. Blacque, T. Fox, C. M. Frech, H. Berke, *Chem. Eur. J*. **2009**, *15*, 2121-2128.
9. Y. Jiang, O. Blacque, T. Fox, C. M. Frech, H. Berke, *Organometallics* **2009**, *28*, 5493-5504.
10. a) Y. Jiang, J. Hess, T. Fox, H. Berke, *J. Am. Chem. Soc*. **2010**, *132*, 18233-18247; b) Y. Jiang, B. Schirmer, O. Blacque, T. Fox, S. Grimme, H. Berke, *J. Am. Chem. Soc*. **2013**, *135*, 4088-4102
11. a) R. R. Schrock, J. A. Osborn, *J. Am. Chem. Soc.* **1976**, *98*, 2134; b) R. R. Schrock, J. A. Osborn, *J. Am. Chem. Soc*. **1976**, *98*, 4450; c) R. H. Crabtree, A. Gautier, G. Giordano, and T. Khan, *J. Organometal. Chem*. **1977**, *141*, 113.
12. a) H. Berke, P. Burger, *Comments Inorg.Chem.* **1994**, *16*, 279-312; b) H. Jacobsen, H. Berke, in *Recent Advances in Hydride Chemistry*; (Ed.: R. Poli), Elsevier: Amsterdam, Holland, **2001**; pp 89-116; c) A. Choualeb, E. Maccaroni, O. Blacque, H. W. Schmalle, H. Berke, *Organometallics* **2008**, *27*, 3474-3481.
13. J. Chatt, S. Coffey, *J. Chem. Soc. A* **196**9,1963-1969.
14. M. L. Clarke, J. J. R. Frew, *Ligand electronic effects in homogeneous catalysis using transition metal complexes of phosphine ligands*; *Organometallic Chemistry*, **2009**, *35*, 19-46.
15. P. W. N. M. van Leeuwen, *Homogeneous Catalysis: Understanding the Art*, Kluwer Academic Publishers, The Netherlands, **2004**.
16. a) M. Kranenburg, Y. E. M. van der Burgt, P. C. J. Kamer, P. W. N. M. van Leeuwen *Organometallics* **1995**, *14*, 3081-3089; b) L. A. van der Veen, P. H. Keeven, G. C. Schoemaker, J. N. H. Reek, P. C. J. Kamer, P. W. N. M. van Leeuwen, M. Lutz, A. L. Spek, *Organometallics* **2000**, *19*, 872-883.
17. Gusev, D.; Llamazares, A.; Artus, G.; Jacobsen, H.; Berke, H.*Organometallics* **1999**, *18*, 75-89.

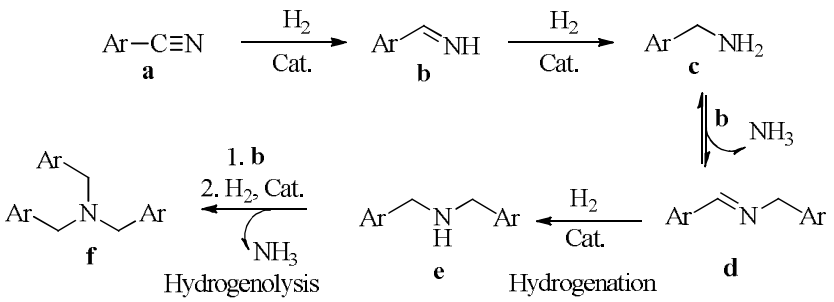
18. B. Dudle, *Thesis*, **2010**, University of Zurich, Switzerland.
19. von Zelewsky, A. Stereochemistry of coordi+nation compounds, In Inorganic Chemistry; Wiley: Chichester, U.K, **1995**.
20. J. Chatt, L. A. Duncanson, *J. Chem. Soc.* **1953**, 2939-2947.
21. C. P. Casey, G. T. Whiteker, *Isr. J. Chem*. **1990**, *30*, 299-304.
22. Crabtree, R. Acc. Chem. Res. **1979**, *12*, 331-337.
23. J. Chatt, S. Coffey, *J. Chem. Soc. A* **1969**, 1963–1969.
24. a) A. Choualeb, O. Blacque, H. W. Schmalle, T. Fox, T. Hiltebrand, H. Berke, *Eur. J. Inorg. Chem.* **2007**, 5246-5261; b) J. A. Gladysz, B. J. Boone, B, *Angew. Chem., Int. Ed. Engl*. **1997**, 36, 550-583; c) A. Choualeb, E. Maccaroni, O. Blacque, H. W. Schmalle, H. Berke, *Organometallics* **2008**, *27*, 3474-3481.
25. a) J. A. Osborn, F. H. Jardine, J. F. Young, G. J. Wilkinson, *Chem. Soc. A* **1966**, *12*, 1711-1732; b) R. R. Schrock, J. A. Osborn, *J. Am. Chem. Soc*. **1976**, *98*, 2134-2143; c) C. R. Landis, J. Halpern, *J. Am. Chem. Soc.* **1987**, *109*, 1746-1754; d) R. H. Crabtree, A. Gautier, G. Giordano, T. Khan, *J. Organomet. Chem.* **1977**, *141*, 113-121.
26. M. W. Haenel, D. Jakubik, E. Rothenberger, G. Schroth, *Chem. Ber*. **1991**, *124*, 1705-1710; b) C. A. Wheaton , B. J. Ireland, P. G. Hayes, *Organometallics* **2009**, *28*, 1282-1285.
27. A. Choualeb, E. Maccaroni, O. Blacque, H. W. Schmalle, H. Berke, *Organometallics* **2008**, *27*, 3474-3481.

Homogeneous Hydrogenations of Nitriles Catalyzed by Rhenium Complexes

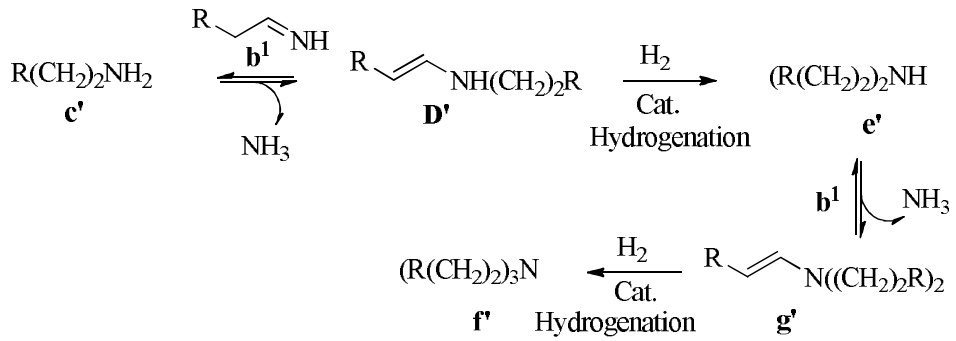
(Major part of this work was published in K. Rajesh, B. Dudle, O. Blacque, H. Berke, *Adv. Synth. Catal.* **2011**, *353*, 1479-1484)

3.1. Introduction

There has been a strong interest in the hydrogenation of nitriles due to their facile access and frequent availability as commodity chemicals, the reaction has great potential in synthetic organic chemistry and in the production of pharmaceuticals, agrochemicals, textile and rubber chemicals.[1] Apart from this aspect, syntheses of secondary amines are particularly significant in view of their role as biologically active molecules[2,3] and versatile ligands.[2,4] However, apart from the difficulty in their hydrogenation,[1] a crucial selectivity problem arises leading to the formation of mixtures of primary, secondary and tertiary amine, as well as intermediate imines.[1a,b,6] Although many proposals on the mechanism of the formation of secondary amines and tertiary amines have been put forward (Scheme 3.1 and Scheme 3.2), it is still unclear whether the reductions to amines occur through the hydrogenation of imines, enamines or the hydrogenolysis of gem-diamines.[1a] But what is mechanistically well



Scheme 3.1. Formation of different types of imines/amines in the hydrogenation of aromatic nitriles.



Scheme 3.2. Formation of different types of imines/amines/enamines in the hydrogenation of aliphatic nitriles

established, is the reaction between the formed primary amine and the intermediate imine accompanied by the expulsion of ammonia, which can give rise to a symmetrical secondary amine and repetition of this type of reaction sequence with the formed secondary amine. This can lead to a symmetrical tertiary amine.[1a,b,6] The composition of the reduction products depends mainly on the nature of the reducing agent, catalyst, reaction temperature and hydrogen pressure, and on the structure of the nitrile.[2]

Catalytic hydrogenation of nitriles using molecular hydrogen is of great interest as it is more efficient, economic and environmental friendly in processes as they have been applied in both academia and industry.[1b,7] The formation of amines is often achieved by heterogeneously[8] or homogeneously catalyzed processes that involve the hydrogenation of Nitriles. The homogeneous processes offer the opportunity for appropriate ligand sphere turning there by imparting improved selectivity and operative at mild conditions as well as understanding of their mechanisms. Homogeneous hydrogenations of nitriles are often achieved using Ni,[9] Ru,[6a,10] Rh,[5b] Pd,[11] Ir[12] and Pt[13] complexes. Alkylamines can also be produced by amination of alcohols over acidic catalysts, however this tends to form also undesired alkenes.[14] Hydroaminomethylation of alkenes,[15] reductive amination of carbonyl compounds, treatment of primary amines with alkyl halides or dialkyl sulfates or sulfonates,

addition of nucleophiles or radicals to N-substituted imines etc., have been widely reported for the synthesis of secondary amines.[3] However, the traditional methods for secondary amine formation are often problematic, because of harsh reaction conditions, generally poor yields and/or low chemoselectivities.[3]

3.2. Results and Discussion

3.2.1. Hydrogenation of Nitriles Catalyzed by Complexs of the Type II, III and VII

We tested the activity of complexes **IIIA**, **IIB** and **VIIA-VIIB** for the hydrogenation of nitriles. All the four complexes were turned out to be catalysts and could hydrogenate nitriles to the corresponding symmetrical secondary or tertiary amines in good selectivity. Although the formation of N-benzylidenebenzylamine **d** was observed in the hydrogenation of benzonitrile, no N-benzylideneamine **b** or benzylamine **c** was detected during the course of the reaction. However, tribenzylamine **f** was observed as a side product. The formation of a considerable amount of N-benzylidenebenzylamine during the course of the reaction and its decrease at the end of the reaction indicated that N,N-dibenzylamine was formed by the hydrogenation of N-benzylidenebenzylamine rather than by hydrogenolysis of the gem-diamine formed by the reaction between **b** and **c**; whereas the formation of additional tribenzylamine is attributed as a consequence of the hydrogenolysis of the gem-diamine. But when the aliphatic nitrile, phenylacetonitrile was subjected to hydrogenation, diphenethyl-2-phenylethenamine **g'** was detected which revealed that the tertiary amine **f'** was formed by hydrogenation of the enamine **g** rather than the hydrogenolysis of gem-diamine.

Hydrogenation of benzonitrile using 0.1 mol% of **VIIA** was carried out under different conditions and the selectivity of formation of various substituted amines are given in Table 3.1). An initial TOF of 90 h^{-1} was observed at 50 bar of hydrogen pressure and 140 °C in THF as solvent (Table 3.1, entry 1). When 25 equivalents of triethylsilane with respect to the amount of the catalyst were added, the TOF was raised to 205 h^{-1} (Table 3.1, entry 3),

Table 3.1. Optimization table for the hydrogenation of benzonitrile[a]

Entry	Et_3SiH[b] [equiv.]	Pressure[bar]/ Catalyst	Selectivity [%][c] after 2 h			Initial TOF [h^{-1}]	Initial Conv.[c] [%/2 h]
			d	**e**	**f**		
1	–	50/**VIIA**	28	72	–	90	18
2	–	50/ **VIIA**	7	80	13	–	90/16 h
3	25	50/ **VIIA**	17	79	4	205	41
4	25	50/ **VIIA**	4	66	30	–	90/18 h
5	5	50/ **VIIA**	8	86	6	161	32
6	50	50/ **VIIA**	11	85	4	208	42
7	25	30/ **VIIA**	7	82	11	135	27
8	25	50/ **VIIA**	33	62	5	79	16[d]
9	25	50/ **VIIA**	7	62	31	156	31[e]
10	25	50/**IIIA**	16	81	3	250	50
11	25	50/**IIIA**	8	73	19	–	91/18 h
12	25	50/**IIB**	17	81	2	229	46
13	25	50/**VIIB**	19	76	5	161	32

[a]0.1 mol% of catalyst was used, reaction at 140 °C in THF, TOFs were calculated as an average of the first 2 h. [b]With respect to catalyst. [c]By GC/MS. [d]Reaction at 120 °C. [e]Solvent: dichloromethane.

Table 3.2. Hydrogenation of phenylacetonitrile and cyclohexanecarbonitrile[a]

Entry	Et_3SiH[b] [equiv.]	Pressure [bar]/ Catalyst	Selectivity [%][c] after 2 h			Initial TOF [h^{-1}]	Initial Conv.[c] [%/2 h]
			D'	**e'**	**f'**		
1	25	50/**VIIA**	–	31	37	248	50[d]
2	25	50/ **VIIA**	–	38	53	–	97[e] [f]
3	25	50/ **VIIA**	17	83	–	150	30
4	25	50/ **VIIA**	1	94	5	–	99[e]

[a]0.1 mol% of catalyst was used, reaction at 140 °C in THF, TOFs were calculated as an average of the first 2 h, entries 1-2 for phenylacetonitrile and 3-4 for cyclohexanecarbonitrile. [b]With respect to catalyst. [c]By GC/MS based on the consumption of the substrate, [d]32% of **g'** was formed. [e]Conversion in 18 h. [f]9% of **g'** was formed.

however, addition of 5 equivalents of triethylsilane was found to be inferior (Table 3.1, entry 5) and addition of 50 equivalents was found to have an effect comparable to the reaction with 25 equivalents of triethylsilane (Table 3.1, entry 6). A TOF of 156 h^{-1} was obtained, when

dichloromethane was used as the solvent, but gave 31% of tribenzylamine (Table 3.1, entry 9). When the reaction was carried out at a pressure of 30 bar of hydrogen, a TOF of 135 h^{-1} was accomplished with the formation of 11% of tribenzylamine (Table 3.1, entry 7), whereas the reaction at 50 bar hydrogen and 120 °C gave a TOF of 79 h^{-1} with the formation of 5% of tribenzylamine (Table 3.1, entry 8). However, still longer reaction times using catalyst **VIIA** with 50 bar of hydrogen pressure at 140 °C and the addition of 25 equivalents of triethylsilane in THF gave 30% of tribenzylamine and 4% of N-benzylidenebenzylamine in 18 h (Table 3.1, entry 4), whereas without the addition of silane, only 13% of tribenzylamine and 7% of N-benzylidenebenzylamine were obtained within 16 h (Table 3.1, entry 2) with 90% conversions in both the cases. Although the initial TOF was comparatively higher, the longer reaction time would be accompanied by the formation of higher amounts of tertiary amine with much prominence in the former case there by reducing the selectivity. Under the former conditions of addition of triethylsilane, reaction with catalysts **IIIA**, **IIB** and **VIIB** gave initial TOFs of 250 h^{-1}, 229 h^{-1} and 161 h^{-1}, respectively (Table 3.1, entries 10, 12 and 13).

The hydrogenation of the aliphatic phenylacetonitrile using catalyst **VIIA** under these conditions gave a TOF of 248 h^{-1}, with a conversion of 50%, but showed selectivity towards triphenethylamine **f'** (Table 3.2, entry 1) and continuing this reaction gave a conversion of 97% with selectivities of 53% of triphenethylamine **f'**, 38% of diphenethylamine **e'** and 9% of diphenethyl-2-phenylethenamine **g'** in 18 h (Table 3.2, entry 2). The selectivity toward the tertiary amine in this case can be due to higher reactivity towards nucleophilic attack on the non-conjugated aliphatic imine functionality. Hydrogenation of the aliphatic cyclohexanecarbonitrile gave a TOF of 150 h^{-1} with a conversion of 30%, but interestingly it showed selectivity towards the secondary amine rather than the tertiary amine (Table 3.2, entry 3), which can be attributed as a consequence of the bulkiness, as well as electron

richness, which is expected to retard the nucleophilic attack on this system. Further runs of this reaction gave a conversion of 99% in 18 h with selectivities of 94% of bis(cyclohexylmethyl) amine **e'** along with 5% of tris(cyclohexylmethyl) amine **f'** and 1% of cyclohexylidene(cyclohexylmethyl) methanamine **D'** (Table 3.2, entry 4).

Keeping the other parameters unchanged, the selectivity of the hydrogenation of benzonitrile was reversed (Table 3.1, entries 2 and 4 in comparison with Table 3.3 entries 1 and 2) with respect to silane with a catalyst loading of 0.5 mol% at a pressure of 75 bar (optimized conditions) gave a TOF of 198 h^{-1} with a conversion of 99% with selectivities of 90% of N,N-dibenzylamine, 4% of tribenzylamine and 6% of the N-benzylidenebenzylamine (Table 3.3, entry 2) in 1 h. However, only very little improvement in hydrogenation was

Table 3.3. Hydrogenation of nitriles under optimized conditions[a]

Entry	Nitrile Ar[b]	Cat.	Selectivity [%][c]			TOF (h^{-1})	Conv. (%)[c]
			d	**e**	**f**		
1	Ph	**VIIA**[d]	10	66	24	180	90
2	Ph	**VIIA**	6	90	4	198	99
3	Ph	**IIIA**	5	85	10	198	99
4	Ph	**IIB**	8	86	6	198	99
5	Ph	**VIIB**	7	82	11	196	99
6	3-Tolyl	**IIIA**	2	89	9	198	99
7	3-Tolyl	**IIB**	4	87	9	198	99
8	2-Thienyl	**VIIA**	5	83	12	162	99
9	2-Thienyl	**VIIIB**	5	85	10	160	99
10	3-Tolyl	**VIIA**	2	81	17	170	99
11	3-Tolyl	**VIIB**	2	80	18	169	99
12	$PhCH_2$	**IIIA**	-	10	85	176	99[e]
13	Cyclohexyl	**IIIA**	2	95	3	198	99

[a]0.5 mol% of catalyst with 25 equiv. of triethylsilane with respect to catalyst at 75 bar H_2, 140 °C in THF, run for 1 h except for entries 8-12 for which reactions were run for 4 h and the given TOFs are for the first hour. [b]Ar = R for entries 12 and 13 which corresponds to scheme 3.2, wherein **d** = **D'**, **e** = **e'**, **f** = **f'** and for entry 13, RCH_2 = cyclohexyl. [c]By GC/MS based on the consumption of the substrate and for entry 2, a quantification using naphthalene as an internal standard was also adopted. [d]No silane was added. [e]5% of **g'** was formed.

observed even after 3 h, but an increased portion of tertiary amine (6%) and a reduced amount of N-benzylidenebenzylamine (4%) was noticed. Under these conditions, reaction in the absence of silane gave a TOF of 180 h^{-1} with 90% conversion forming 66% of N,N-dibenzylamine, 24% of tribenzylamine and 10% of N-benzylidenebenzylamine in the first 1 h (Table 3.3, entry 1). The generality of the reaction was then tested by applying all the other catalysts in the benzonitrile reduction and reductions of a few other nitriles under the given optimized condition (Table 3.3).

To exclude any heterogeneous reaction course in the hydrogenation catalyses, filtration and mercury poisoning experiments were carried out.[20] The hydrogenation of benzonitrile was carried out using catalyst **VIIA** under the conditions of Table 3.3. The reaction was stopped at 20 min and the obtained clear pale yellow solution, which showed a conversion of 71%, was filtered through a plug of celite into a new vessel with a new stirring bar, and the reaction was continued for another 40 min under the same conditions showed identical results to Table 3.3, entry 2. Mercury poisoning experiment was carried out on the hydrogenation of benzonitrile using catalyst **VIIA** under the conditions of Table 3.3. In the presence of 60 equiv. of Hg (per Re atom) the reaction again showed identical results to Table 3, entry 2. The filtration and mercury poisoning tests were thus all negative which rule out any colloid or amalgam formation. At this point, it is also worth mentioning that rhenium metal has a very high atom binding energy (second largest in the Periodic Table of Elements) possessing therefore low propensity for colloid or amalgam formation.

3.2.2. Mechanistic Studies

As a step to elucidate the mechanism of this transformation, in a Young NMR tube complex **IIIA** was reacted with 2 bar H_2 pressure at 100 °C in dichloromethane for 2 h. Analysis of this sample showed mixture of products according to ^{31}P NMR spectroscopy. However, leaving the sample for a week led to the formation of single crystals suitable for X-ray

diffraction studies. This was thus analyzed to be the complex **XVIA** where the CH_3CN ligand in **IIA** (from which the dinuclear complex **IIIA** was formed; Chapter 2) was replaced by a NH_3 ligand (Figure 3.1). The formation of NH_3 further provided evidence for the ability of this complex to hydrogenate nitriles to secondary or tertiary amines. Acetonitrile was hydrogenated completely to ethylamine, which reacted with the intermediate acetylimine to form imines or amines of a higher degree of substitution expelling thereby ammonia, which then coordinated to the rhenium center. Since stoichiometric quantities of ammonia could not

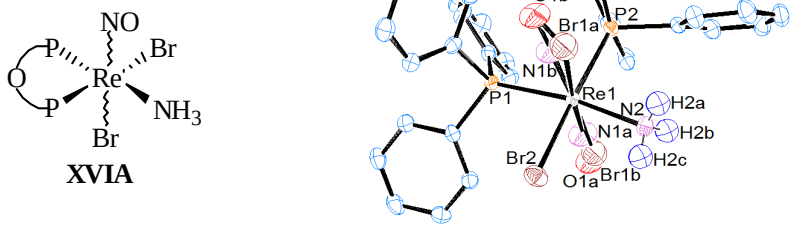


Figure 3.1. Complex **XVIA** and its molecular structure. Anisotropic displacement parameters are depicted at the 50% probability level. Hydrogen atoms and solvent molecules are omitted for clarity. Selcected bond lengths: Re1-Br1a: 2.487(1), Re1-Br2: 2.6065(7), Re1-N2: 2.200(4). Selected bond angles: P1ReP2: 96.10(4).

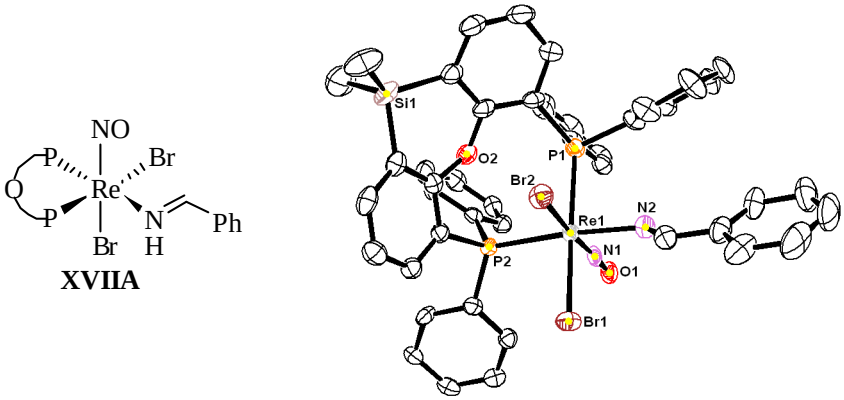


Figure 3.2. Complex **XVIIA** and its molecular structure. Anisotropic displacement parameters are depicted at the 50% probability level. Hydrogen atoms and solvent molecules are omitted for clarity. Selected bond angles: P1ReP2: 96.19(7). Selected bond lengths: Re1-Br1: 2.598(1), Re1-Br2: 2.5785(9), Re1-N2: 2.139(6).

have formed with respect to **IIIA**, we expected that imines and amines could be found to be coordinated to the rhenium centre similar to ammonia in **XVIA**.

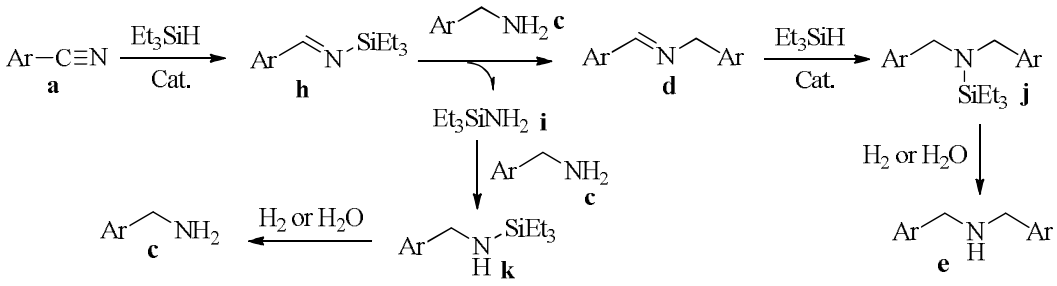
Complex **IIIA** was then reacted in a pressure tube with 2 equiv. of benzonitrile under 2 bar H_2 pressure at 140 °C in THF for 2 h. When cooled to room temperature and left for a week, tiny crystals were seen. This was subjected to an X-ray diffraction study showing a molecular structure of **XVIIA** bearing a N-benzylideneamine ligand formed through partial hydrogenation of benzonitrile (Figure 3.2).

These experiments showed the ability of complexes **IIIA** and **IIB** to hydrogenate nitriles without any co-catalyst. The obtained structures from the stoichiometric reactions suggest that a mechanism, which often require only one vacant site on the metal centre[16] or the dissociation of either a bromide ligand or a phosphine moiety would be operative. However, an ionic mechanism for the splitting of H_2 seems less probable could be ruled out since these complexes were found to be active also in the hydrogenation of olefins and the hydrogenation of olefins is not expected to be operative through heterolytic splitting of H_2. Further details will be explored in chapter 4.

The reactions using **IIIA** or **IIB** as a catalyst in the presence of Et_3SiH**,** as well he reactions using **VIIA** or **VIIB** as a catalyst in the presence or absence of Et_3SiH, are presumably be operating through a catalytic cycle as described for the hydrogenation of olefins (Chapter 2) with complex of the type **V** as the active species, but starting from an η^1-coordinated nitrile to the rhenium centre.

It is worth mentioning at this stage that in the absence of H_2, i.e. the reaction between Et_3SiH and aromatic nitriles in the presence of **IIIA** or **VIIA** revealed at 80 °C mono hydrosilylation products (Chapter 9). This reaction was far less efficient for the aliphatic nitriles. However, we could not detect any hydrosilylated products under hydrogenation

conditions discussed in this chapter. Thus, an alternative pathway for the formation of higher substituted imines through the activated N-silylimines is depicted in Scheme 3.3.



Scheme 3.3. Influence of hydrosilylation in the hydrogenation of aromatic nitriles.

3.3. Conclusion

In conclusion, we have developed an efficient air stable homogeneously rhenium-catalyzed hydrogenation of nitriles with good selectivities for symmetrical secondary amines or tertiary amines. Addition of triethylsilane could increase the TOFs and suppress overalkylation of the amines at higher pressure with a relatively high loading of the catalyst. Secondary amines are anticipated to be formed by the hydrogenation of the imine (for aryl nitriles) or enamine (for alkyl nitriles) intermediates generated by the elimination of ammonia from the *gem*-diamine species whereas the tertiary amines were formed by the hydrogenolysis of the *gem*-diamines (for aryl nitriles) or hydrogenation of the enamines (for alkyl nitriles). Rhenium as a neighbouring element to precious metals can be ligand sphere tuned to adopt similar catalytic properties providing an appropriate alternative to precious metal catalyses.

3.4. Experimental Section

3.4.1. General procedure for the catalytic hydrogenation of benzonitrile

Catalyst **VIIA** (0.002 g, 2.18 $\times 10^{-3}$ mmol) was taken in a stainless steel autoclave and was added benzonitrile (0.045 g, 0.44 mmol) followed by THF (0.2 mL) and triethyl silane (9 µL, 5.63×10^{-2}) Naphthalene (0.028 g, 0.22 mmol) was added as internal standard. It was pressurized with 75 bar of hydrogen and kept in an oil bath

maintained at 140 °C. After appropriate reaction time, the vessel was immediately cooled to room temperature and the hydrogen was released slowly in a fume hood. The reaction mixture was filtered through a short plug of silica gel and the ratio of product and conversion were measured by GC/MS (CP-3800 Saturn 2000MS/MS spectrometer, column: Agilent VF-5ms, 30m x 0.25mm x 0.25µm).

GC/MS data for nitriles, imines and amines

Nitrile	Nitrile		Imine		Enamine		Secondary Amine		Enamine		Tertiary Amine	
	a/a'		d		D'		e/e'		g'		f/f'	
	rt	m/z	rt	m/z	rt	m/z	rt	m/z	rt	m/z	rt	m/z
Benzonitrile	2.90	103.1	8.15	195.0	-	-	7.87	197.1	-	-	10.65	287.1
3-methyl-benzonitrile	3.64	117.0	9.03	224.0	-	-	8.80	226.3	-	-	11.45	329.0
Thiophene-2-carbonitrile	3.03	109.0	8.43	208.0	-	-	8.04	209.8	-	-	11.01	304.9
Phenyl acetonitrile	4.12	117.0	-	-	-	-	8.85	227.3	13.07	328.2	12.10	330.2
Cyclohexane carbonitrile	3.80	109.8	-	-	7.19	208.2	7.43	210.3	-	-	10.08	304.5

3.5. References

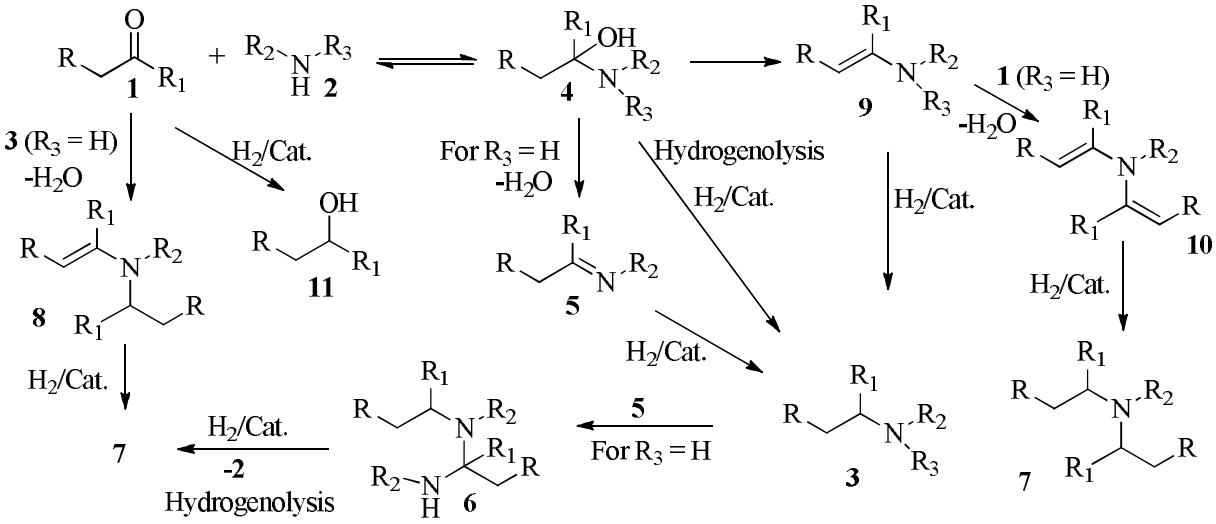
1. a) S. Gomez, J. A. Peters, T. Maschmeyer, *Adv. Synth. Catal.* **2002**, *344*, 1037-1057; b) B. Chen, U. Dingerdissen, J. G. E. Krauter, H. G. J. L. Rotgerink, K . Mobus, D. J. Ostgard, P. Panster, T. H. Riermeier, S. Seebald, T. Tacke, H. Trauthwein, *Appl. Catal. A: Gen*. **2005**, *280*, 17-46;
2. A. Galan, J. de Mendoza, P. Prados, J. Rojo A. M. Echavarren, *J. Org. Chem.* **1991**, *56*, 452-454.
3. a) R. N. Salvatore, C. H. Yoon, K. W. Jung, *Tetrahedron* **2001**, *57*, 7785-7811; and see reference therein; b) M. Freifelder, *Catalytic Hydrogenation in Organic Synthesis: Procedures and Commentary*; (Wiley: New York, **1978**; Chapter 10).
4. a) R. A. Grey, G. P. Pez, A. Wallo, *J. Am. Chem. Soc*. **1981**, *103*, 7536-7542; b) T. Yoshida, T. Okano, S. Otsuka, *J. Chem. Soc., Chem. Commun.* **1979**, 870-871
5. a) B. Miriyala, S. Bhattacharyya, J. S. Williamson, Tetrahedron, **2004**, *60*, 1463-1471; b) A. Togni, L. M. Venanzi, *Angew. Chem. Int. Ed*. **1994**, *33*, 497-526; c) M. Sawamura, Y. Ito, *Chem. Rev*. **1982**, *92*, 857-871.
6. R. Reguillo, M. Grellier, N. Vautravers, L. Vendier, S. Sabo-Etienne, *J. Am. Chem. Soc*. **2010**, *132*, 7854-7855; d) J. von Braun, G. Blessing, F. Zobel, *Ber. Dtsch. Chem. Ges*. **1923**, *56*, 1988-2001; e) G. Mignonac, *Comptes Rendus* **1920**, *171*, 14.
7. H.-U. Blaser, M. Studer, *Appl. Catal. A: Gen*. **1999**, *189*, 191-204.
8. a) L. Hegedus, T. Mathe, T. Karpati, *Appl. Catal. A: Gen.* **2008**, *349*, 40-45; b) L. Hegedus, T. Mathe, *Appl. Catal. A*, **2005**, *296*, 209-215; c) P. Kukula, M. Studer, H.-U. Blaser, *Adv. Synth. Catal*. **2004**, *346*, 1487-1493.

9. a) P. Zerecero-Silva, I. J.-Solar, M. G. Crestani, A. Arevalo, R. Barrios-Francisco, J. J. Garcia, *Appl. Catal. A: Gen.* **2009**, *363***,** 230-234; b) B.W. Hoffer, J. A. Moulijn, *Appl. Catal. A: Gen.* **2009**, *352*, 193-201.
10. a) D. Addis, S. Enthaler, K. Junge, B. Wendt, M. Beller, *Tetrahedron Lett.* **2009**, *50*, 3654-3656; b) S. Enthaler, D. Addis, K. Junge, G. Erre, M. Beller, *Chem. Eur. J.* **2008**, *14*, 9491-9494. c) D. K. Mukherjee, B. K. Palit, C. R. Saha, *J. Mol. Catal.* **1994**, *88*, 57-70.
11. A. Bose, C. R. Saha, *J. Mol. Catal.***1989**, *49*, 271-283.
12. C. S. Chin, B. Lee, *Catal. Lett.* **1992**, *14*, 135-140.
13. F.R. Hartley, *The Chemistry of Platinum and Palladium,* (Applied Science Publishers, London, **1973**).
14. K. S. Hayes, *Appl. Catal. A: Gen.* **2001**, *221*, 187-195.
15. A. Seayad, M. Ahmed, H. Klein, R. Jackstell, T. Gross, M. Beller, *Science* **2002**, *297*, 1676-1678.
16. R. M. Bullock, in *The Handbook of Homogeneous Hydrogenation* (ed.: J. G. de Vries and C. J. Elsevier), Wiley-VCH Verlag GmbH, Weinheim, Germany, **2008**, Ch. 7.

Rhenium Catalyzed Highly Efficient Homogeneous Direct Reductive Amination of Aldehydes and Hydrogenation of Imines Based on Reversible Halide Dissociation

4.1. Introduction

When aldehydes or ketones are reacted with ammonia or primary amines, carbinolamines, imines or enamines may be formed and when they are reacted with secondary amines, carbinolamines or enamines are obtained, which are subsequently reduced to primary, secondary and tertiary amines, respectively. Such processes are called reductive amination with respect to the carbonyl compound or reductive alkylation with respect to the amine. The reaction is a versatile tool in synthetic organic chemistry for the preparation of various amines, other synthetic intermediates, pharmaceuticals, agrochemicals and rubber chemicals.[1] Several borohydrides,[2a-t] silyl hydrides in combination with metal catalysts[3] or organocatalysts[4] or acids,[5] metal hydrides,[6] metal acids[7] and transition metal complexes with formate salts,[8] Hantzsch dihydropyridines,[9] as well as benzothiazoline[10] etc, have been reported as reducing agents for the reductive amination of aldehydes and ketones. However, most of these reagents have one or more drawbacks, like the use of stoichiometric amounts of the reagents, toxicity of these, side reactions, harsh reaction conditions, the requirement of application of excess amine or ammonia and difficult work-up procedures.[2b,11] Treatment of primary amines with alcohols, alkyl halides, dialkyl sulfates or sulfonates comprise alternative N-alkylations, addition of nucleophiles or radicals to N-substituted imines were often reported as alternative syntheses of secondary amines, but all these methods still hold



Scheme 4.1. General scheme for the formation of various amines/imines/enamines in the reductive amination of aldehydes or ketones.

any of the above mentioned drawbacks.[11] Catalytic reductive aminations using molecular hydrogen are of great interest as they are more efficient, economic and environmentally friendly in their conversions and are suitable to both academic laboratories and industry.[1,13a-c] Preliminary studies began in 1974 when Mark′o and Bakos reported the first example using molecular H_2 applying Co and Rh carbonyl complexes as catalysts.[13d] Further then, especially in the last decade many reports arose including asymmetric versions, which apply homogeneous transition metal based hydrogenations.[13] However, many of these methods require harsh reaction conditions and the catalytic treatments suffer from low selectivity, because of low tolerance to functionalities. For instance, groups like $–NO_2$ or electron poor heterocycles were not seem to react or survive, or were not studied under these reaction conditions.

A typical problem facing the reductive amination is the reduction of the carbonyl group before it condenses with the amine or ammonia.[1a-b,5,13b] Generation of over-alkylation products may also be a major issue in this reaction (Scheme 4.1).

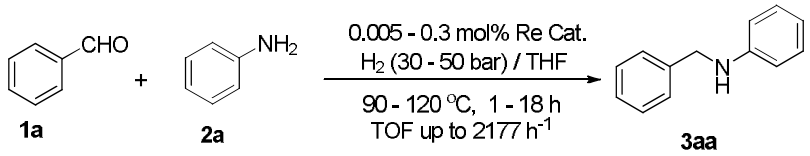
4.2. Results and Discussion

4.2.1. Reductive Amination of Aldehydes Using Complexes of the Type II, III and VII

Following the development of rhenium(I) complexes, which showed remarkable activities in hydrogenations of olefins (Chapter 2) and nitriles (Chapter 3) we studied their activity towards direct reductive aminations of aldehydes, as well as the hydrogenation of imines using molecular hydrogen. The reductive amination of aldehydes utilizes equimolar amounts of aldehyde and amine in THF, which can give up to 97% yield of the desired secondary amines during hydrogenation with relatively low catalyst loadings. To study a representative example, stoichiometric amounts of benzaldehyde (**1a**) and aniline (**2a**) were subjected to reductive amination with 0.005 mol% of the catalyst **IIIA** under a pressure of 30 bar H_2 and at a temperature of 120 °C in THF. N-benzylaniline (**3aa**) was obtained with a TOF of 2177 h^{-1} without formation of benzyl alcohol, but 1% of N,N-dibenzylaniline appeared with 14% conversion during the first hour. The reaction showed a conversion of 97% in 18 h with formation of 16% of N-benzylaniline (**3aa**), 75% of the tertiary N,N-dibenzylaniline (**7aa**) and 6% of the *gem*-diamine **6aa** (Table 4.4.1, entry 1). In order to improve the selectivity for the desired secondary amine **3aa**, the reaction was carried out with 0.1 mol% catalyst loading under a pressure of 50 bar and at 90 °C; a TOF of 559 h^{-1} in the first hour was noticed, which gave 95% yield of the desired product **3aa** in 3 h with 3% of benzyl alcohol (Table 4.4.1, entry 2). It is worth mentioning that similar results were obtained when a mixture of **IIA** and **IIIA** (~ 2:1 mixture obtained directly after preparation) was used as the catalyst instead of only **IIIA**. Apart from the desired product, the major reaction component during sampling was found to be the corresponding imine **5aa** (>95%). Thus, it became evident that N-benzylaniline (**3aa**) was formed via the intermediacy of the imine **5aa**, which became hydrogenated, rather than via hydrogenolysis of the carbinolamine **4aa**. However, the hydrogenolysis of **4** to form **3** is expected to be the route when aldehydes, which do not

possess α-hydrogen atoms, are subjected to this reaction with secondary amines. The formation of N,N- dibenzylaniline (**7aa**) can be envisaged as a consequence of the hydrogenolysis reaction of the *gem*-diamine **6aa** formed by the reaction between the imine **5aa** and N-benzylaniline (**3aa**), rather than by the reaction between **3aa** and benzaldehyde followed then by hydrogenolysis, which was indicated by generation of only < 3% of benzaldehyde (Scheme 4.1). On attempts to understand the efficiency of the catalyst toward the production of the desired product **3aa**, the catalyst loading was adjusted to 0.05 mol% under 50 bar of H_2 pressure at 90 °C (optimized condition), which showed a TOF of 762 h^{-1} in the first hour with the same results as with 0.1 mol%, but in 6 h (Table 4.4.1, entry 3). Further attempts to optimize the selectivity of the reaction did not lead to better results.

Table 4.4.1. Reductive amination of benzaldehyde with aniline.[a]



Entry	Cat./mol%	P(bar)/ T(°C)	Time (h)	TOF (h^{-1}) (1^{st} h)	Yield (%) (**3ab**)	Yield (%) (**6aa/7aa**)	Yield (%) (**11a**)	Conv. (%)
1	**IIIA**/0.005	30/120	18	2177	16	6/75	-	97
2	**III**/0.1	50/90	3	559	95	-/-	3	99
3	**IIIA**/0.05	50/90	6	762	95	-/-	3	99
4	**IIIA**/0.05	30/120	3	1095	66	10/13	6	95
5	**IIIA**/0.05	50/120	2	1519	81	4/7	5	97
6	**IIIA**/0.1	50/120	<1	>960	96	-/-	3	99
7	**IIB**/0.05	50/90	7	746	96	-/-	3	99
8	**VIIA**/0.05	50/90	6	557	95	-/-	3	99
9	**VIIB**/0.05	50/90	7	541	95	-/-	3	99
10	**IIIA**/0.05	50/90	4	1066	96	-/-	3	99[b]

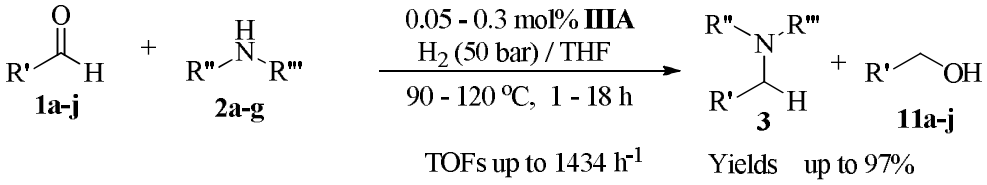
[a]Yield, conversion and selectivity by GC/MS based on the consumption of aldehydes or aniline; TOFs for the formation of tertiary amines are excluded; reactions were carried out in THF. [b]100 equivalents of *n*-Bu_4NBr with respect to catalyst was added.

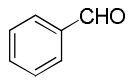
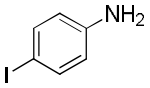
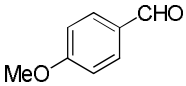
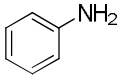
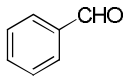
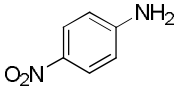
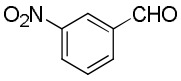
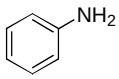
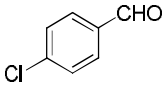
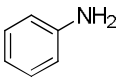
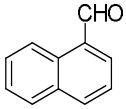
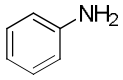
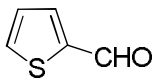
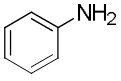
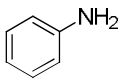
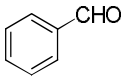
Applying the same loading of the catalyst, under 30 bar H_2 at 120 °C the reaction showed a TOF of 1095 h^{-1} with formation of 1% of benzyl alcohol and 2% of the tertiary amine **7aa** in 55% conversion in the first hour, but gave only 66% yield of the desired product **3aa**, 13% yield of the tertiary amine **7aa**, 10% yield of the *gem*-diamine **6aa** along with 6% of benzyl alcohol in 95% conversion in 3 h (Table 4.4.1, entry 4). Continuation of this reaction for another 3 h showed an increase in the tertiary amine **7aa** to 30% and decrease in both the *gem*-diamine **6aa** and the desired product **3aa** to 5% and 48% respectively, with a conversion of 97%. This further confirmed that the formation of the tertiary amine, N,N-dibenzylamine (**7aa**) proceeded via the *gem*-diamine **6aa**. Another run of the reaction with a pressure of 50 bar H_2 at 120 °C showed an initial TOF of 1519 h^{-1}, but gave only 81% of the desired product **3aa** along with 7% of the tertiary amine **7aa**, 4% of the *gem*-diamine **6aa** and 5% of benzyl alcohol with 97% conversion in 2 h (Table 4.4.1, entry 5). At this temperature, a still higher loading of the catalyst (0.1 mol%) furnished 96% of the desired product **3aa** along with 3% of benzyl alcohol with almost complete conversion (Table 4.4.1, entry 6). Under optimized conditions catalyst **IIB** bearing phenyl groups on the silicon atom of the diphosphine ligand furnished a TOF of 746 h^{-1} in the first hour giving rise to the desired N-benzylaniline (**3aa**) in 96% yield along with 3% of the benzyl alcohol as a side-product and 99% total conversion (Table 4.4.1, entry 7). The related ortho metallated rhenacyclic complexes **VIIA** and **VIIB** showed TOFs of 557 h^{-1} (Table 4.4.1, entry 8) and 541 h^{-1} (Table 4.4.1, entry 9), respectively, in the first hour, also with a conversion of 99%, along with 3% of benzyl alcohol and a yield of 95% to the desired product **3aa** in both the cases.

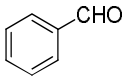
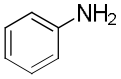
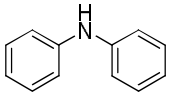
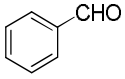
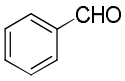
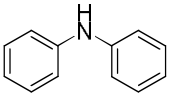
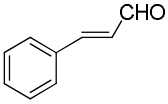
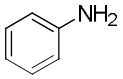
The generality of this reductive amination reaction was then tested with a variety of aldehydes and amines in the presence of catalyst **IIIA (**Table 4.4.2). Reductive amination of benzaldehyde with the electron rich 4-iodoaniline showed a TOF of 1434 h^{-1} in the first hour with 62% yield of the desired product **3ab**, but underwent deiodination of both the imine and

the product when run for the extended period of time of 15 h giving rise to 2% of the corresponding iodide-free imine, N-benzylideneaniline (**5aa**), 90% of the deiodinated secondary amine N-benzylaniline (**3aa**) and 4% of the deiodinated tertiary amine, N-N-dibenzylaniline (**7aa**), over all with a conversion of 96% (Table 4.4.2, entry 1). The electron rich 4-anisaldehyde furnished upon reductive anilation a TOF of 1107 h^{-1} in the first hour with 96% yield of the desired amine N-(4-methoxybenzyl)aniline (**3ba**) in 3 h along with 3% of 4-methoxybenzyl alcohol (Table 4.4.2, entry 2). The electron deficient 4-nitroaniline upon reductive alkylation with benzaldehyde showed an initial TOF of 376 h^{-1} giving rise to 92% yield of the desired product, N-benzyl-4-nitroaniline (**3ac**) along with 4% of benzyl alcohol (**11a**) in 9 h (Table 4.2, entry 3). At a higher loading of 0.3 mol% of catalyst **IIIA** at 120 °C the reductive anilation of the electron deficient aldehyde, 3-nitrobenzaldehyde provided an initial TOF of 171 h^{-1} giving rise to the desired amine, N-(3-nitrobenzyl)aniline (**3ca**) in 94% yield along with 3% of 3-nitrobenzyl alcohol in 15 h (Table 4.2, entry 4). Thus, it became evident that imines bearing an electron deficient aldehydic part were much more difficult to hydrogenate when compared to substrates with an electron deficient amine part. Under optimized conditions, reductive anilation of 4-chlorobenzaldehyde did not provide complete conversion even at the higher temperature of 120 °C run for 24 h so that a higher catalyst loading of 0.15 mol% was considered in combination with a temperature of 90 °C. This gave an initial TOF of 135 h^{-1} with 94% yield of the desired amine, N-(4-chlorobenzyl)aniline (**3da**) and 4% of 4-chlorobenzyl alcohol in 15 h (Table 4.2, entry 5). A higher loading of 0.2 mol% of **IIIA** showed in the case of 1-napthaldehyde a TOF of 84 h^{-1} and a yield of 91% of the desired amine, N-(1-naphthylmethyl)aniline (**3ea**) and 4% of 1-naphthalene methanol in 15 h (Table 4.2, entry 6). By reductive anilation the heterocyclic 2-thienylcarboxaldehyde was converted smoothly into the desired amine under optimized conditions with an initial

Table 4.2. Reductive amination of various aldehydes with different amines using complex **IIIA**[a]



Entry	Aldehyde (**1**)	Amine (**2**)	**IIIA** (mol%)	Time (h)	TOF (1^{st} h)	Yield **3** (%)[b]		Conv. (%)
1	**1a** 	**2b** 	0.05	1	1434	**3ab**	62	63
				15	-	**3aa**	-	96[c]
2	**1b** 	**2a** 	0.05	3	1107	**3ba**	96	99
3	**1a** 	**2c** 	0.05	9	376	**3ac**	92	97
4	**1c** 	**2a** 	0.30	15	171	**3ca**	94	97[d]
5	**1d** 	**2a** 	0.15	15	135	**3da**	94	98
6	**1e** 	**2a** 	0.20	15	84	**3ea**	91	95
7	**1f** 	**2a** 	0.05	4	871	**3fa**	97	99
8	**1g** 	**2a** 	0.10	1	338	**3ga**	34	91[d,e]
9	**1a** 	**2d** 	0.10	15	178	**3ad**	94	96[d]

10	**1h**		**2d**		0.20	15	37	**3hd**	76	99[d,f]
11	**1a**		**2e**		0.10	15	-	**3ae**	-	92[d,g]
12	**1i**		**2a**		0.05	10	-	**3ia**	68	76[d,h,i]
13	**1i**		**2f**		0.20	15	-	**3if**	77	77[i]
14	**1a**		**2g**		0.05	1	620	**3ag**	31	97
15	**1a**		**2f**		0.05	8	224	**3af**	22	97
16	**1j**		**2a**		0.05	15	164	**3ja**	66	96[j]

[a]Unless and otherwise mentioned, all reactions were carried out under 50 bar of H_2 at 90°C in THF; yield and conversion by GC/MS based on the consumption of amine or aldehyde. [b]Unless otherwise mentioned, remaining is the corresponding alcohol. [c]All deiodination products; 90% N-benzylaniline (**5aa**) along with 4% of tertiary amine N,N-dibenzylaniline (**7aa**), remaining being the imine **5aa**. [d]Reaction was carried out at 120 °C. [e]Other products were higher amines, imines, enamines etc. [f]6% of isomeric imine **9** and 15% of **10** were formed. [g]Reaction was carried out in 7 N methanolic ammonia, 43% of benzylidenebenzylamine was formed. [h]8% of N,N-dimethylaniline was formed. [i]Paraformaldehyde was used. [j]8% of N-(3-phenylpropyl)aniline and 10% of 3-phenylpropanal were formed.

TOF of 871 h^{-1} and a yield of 97% of the desired amine, N-(2-thienylmethyl)aniline (**3fa**) along with 2% of the corresponding alcohol in 4 h (Table 4.2, entry 7). The aliphatic isobutyraldehyde was reductively anilated with a catalyst loading of 0.1 mol% at the higher temperature of 120 °C accomplishing a TOF of 338 h^{-1} and a yield of 34% of the desired amine, N-isobutylaniline (**3ga**) in one hour (Table 4.2, entry 8). Reductive amination of benzaldehyde with the aliphatic 1-hexylamine proceeded smoothly with a catalyst loading of 0.1 mol% at atemperature of 120 °C revealing an initial TOF of 178 h^{-1} and a yield of 94% of

the desired amine, N-benzyl-1-hexylamine **3ad** along with 2% of benzyl alcohol in 10 h (Table 4.2, entry 9). Reductive amination of the aliphatic aldehyde, hexanal with aliphatic amine, 1-hexylamine showed a TOF of 37 h^{-1} in the first hour giving rise to a yield of 76% of the desired secondary amine, N,N-dihexyl-1-amine (**3hd**) in 15 h with 99% conversion, when a catalyst loading of 0.5 mol% was chosen at 120 °C (Table 4.2, entry 10). 6% of the isomeric imine **9hd** was also formed at the end of the reaction which was observed only in traces when sampling was done in the first hour. Reductive amination with an ammonia solution in methanol (7 N, 8 equiv.) showed no yield of the desired benzylamine in 15 h, instead 43% of the benzylamine formed was transformed further with benzaldehyde or benzylideneamine to yield benzylidenebenzylamine apart from 6% benzyl alcohol (Table 4.2, entry 11). An excess of paraformaldehyde (2 equiv.) was used at 120 °C for the reductive methylation of aniline. A yield of 68% of N-methylaniline (**3ia**) and 8% of N,N-dimethylaniline was obtained, all with respect to aniline, 24% of aniline remained due to the concomitant hydrogenation of formaldehyde to methanol (Table 4.2, entry 12). Under the same conditions, a still higher loading (3 equiv.) of paraformaldehyde with 0.2 mol% of the catalyst was adopted accomplishing reductive methylation of diphenylamine to give 77% yield of the desired tertiary amine, N,N-diphenylmethylamine (**3if**) in 15 h, all with respect to diphenylamine (Table 4.2, entry 13). Reductive amination of equimolar benzaldehyde with the secondary amines piperidine and diphenylamine gave only 31% and 22% yield, respectively, of the desired tertiary amines, N,N-diphenylbenzylamine (**3ag**) and N-benzylpiperidine (**3af**), due to prevailing hydrogenation of benzaldehyde to benzyl alcohol (Table 4.2, entries 14, 15). α,β-unsaturated *trans*-cinnamaldehyde showed upon reductive anilation specific formation of the desired enamine, N-(3-Phenyl-2-propenyl)benzenamine (**3ja**) in the first hour with 16% conversion, but showed reduced selectivity with 66% yield of

the product **3ja** along with 8% of N-(3-phenylpropyl)benzenamine and 10% of 3-phenylpropanal when run for 15 h (Table 4.2, entry 16).

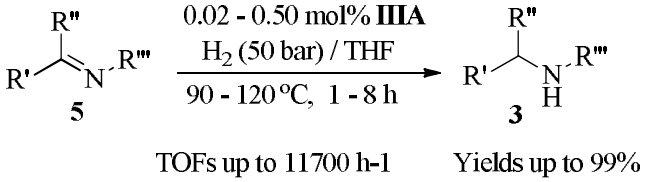
4.2.2. Hydrogenation of Imines Using Complexes of the Type IIIA and XIIIA

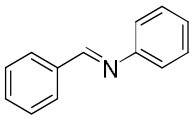
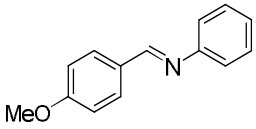
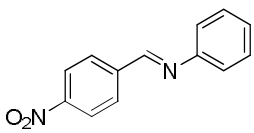
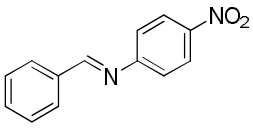
Following the reductive amination of aldehydes which led to the intermediacy of imines, we tested **IIIA** for the hydrogenation of imines including few involved in the reductive amination process discussed above (Table 4.3). Hydrogenation of N-benzylideneaniline **5aa**, was carried out with a loading of 0.05 mol% of **IIA** and under 50 bar H_2 pressure at 90 °C in THF to reveal 99% yield of the desired amine **3aa** within one hour. Consequently, the monitoring samples of this imine hydrogenations were taken in the first 0.25 h. Under the same conditions, but at a relatively lower loading of only 0.02 mol% of complex **IIIA** showed a TOF of 3910 h^{-1} in the first 0.25 h giving rise to 97% yield of the desired product **3aa** in < 3 h (Table 4.3, entry 1). The comparatively low activity in the reductive amination when compared to the imine hydrogenation would be due to several reasons. Apart from the concomitant hydrogenation of the aldehydes to the corresponding alcohols, reversible or irreversible coordination of the aldehydes, as well as its hydrogenated product, alcohols to the catalyst can slow down the catalytic cycle by competitive inhibition. Also, apart from the presence of amines at least in quantities equivalent to the alcohols, other physical and chemical influences of nearly equimolar quantities of water in the reaction medium could reverse the imine formation particularly at higher temperatures. At this point it seems noteworthy to mention that the largest asymmetric catalytic process of the synthesis of the herbicide, (*S*)-Metolachlor, involves the asymmetric hydrogenation of an imine, which in reductive aminations was found to be of comparatively low efficieny.[13e]

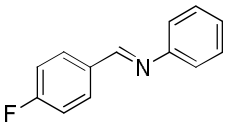
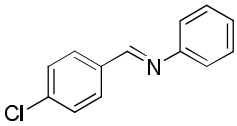
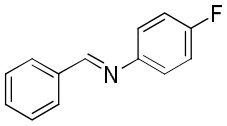
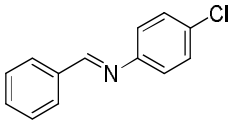
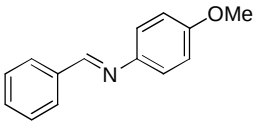
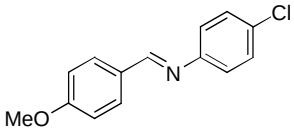
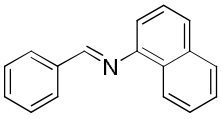
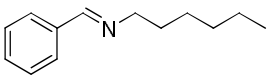
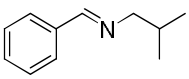
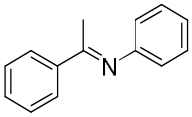
To establish a preference for the imine hydrogenation over the reductive amination, the hydrogenations of various other imines were carried out, which in all cases showed

superior results over their corresponding reductive aminations. Hydrogenation of N-(4-methoxybenzylidene)aniline with 0.02 mol% of **IIIA** showed a TOF of 11700 h^{-1} in the first 0.25 h giving rise to 98% yield of the desired product **3ba** within one hour (Table 4.3, entry 5). At a temperature of 120 °C, the electron deficient N-(4-nitrobenzylidene)aniline was subjected to hydrogenation with 0.1 mol% of **IIIA** as catalyst, in which the tertiary amine **7ka** was observed as side product, so that a higher catalyst loading of 0.5 mol% was adopted,

Table 4.3. Hydrogenation of various imines.[a]



Entry		Imine (**5**)	**IIIA** (mol%)	Time (h)	TOF (h^{-1})	**3**	Yield (**3**, %)
1			0.02	3	3900[b]		97
2	**5aa**		0.02	< 1	8122[b]	**3aa**	97[c]
3			0.02	2	4957[b]		97[d]
4			0.02	< 4	2200[b]		97[e]
5	**5ba**		0.02	< 1	11700[b]	**3ba**	99
6	**5ka**		0.50	< 1	> 192	**3ka**	96[f]
7	**5ac**		0.1	< 3	333	**3ac**	99

8	**5la**		0.1	< 1	2070 [b]	**3la**	99
9	**5da**		0.1	< 3	1012 [b, g]	**3da**	97
10	**5ah**		0.1	< 1	2810 [b, g]	**3ah**	99
11	**5ai**		0.1	< 2	1555 [b, g]	**3ai**	98[g]
12	**5aj**		0.02	< 1	7760 [b, g]	**3aj**	97
13	**5bi**		0.02	< 2	2425	**3bi**	98
14	**5aj**		0.10	< 1	950	**3aj**	95[e]
15	**5ad**		0.15	6	106	**3ad**	95[e]
16	**5ak**		0.15	8	79	**3ak**	95[e]
17	**5ma**		0.5	< 2	198	**3ma**	99[e]

[a]Unless otherwise mentioned, all reactions were carried out in THF under 50 bar H_2 pressure at 90 °C; TOF and yield by GC/MS. [b]In the first 0.25 h. [c]100 equiv. of *n*-Bu_4NBr was added. [d]50 equiv. of *n*-Bu_4NBr was added. [e]**XIIIA** was used as catalyst. [f]Reaction was carried out at 120 °C. [g]TOF by ^1H NMR spectroscopy based on the consumption of imine.

which showed a TOF of > 192 h^{-1} and gave rise to a yield of 96% of the desired product **3ka** within one hour (Table 4.3, entry 6). Like in the corresponding cases of reductive aminations, imines bearing an electron deficient amine part, like N-benzylidene-4-nitroaniline showed better activities even at the lower temperature of 90 °C in comparison with imines with an electron deficient aldehyde part (Table 4.3, entry 7). At this temperature of 90 °C, N-(4-fluorobenzylidene)aniline could be smoothly converted to the corresponding amine with 0.1 mol% loading of **IIIA** revealing a TOF of 2070 h^{-1} in the first 0.25 h and a yield of >99% of the desired product **3la** in < 1 h (Table 4.3, entry 8). Under these conditions, N-(4-chlorobenzylidene)aniline showed a TOF of 1012 h^{-1} in the first 0.25 h giving rise to 97% yield of the desired product **3da** in < 3 h (Table 4.3, entry 9). Under these conditions, N-benzylidene-4-fluoroaniline showed a TOF of 2780 h^{-1} in the first 0.25 h giving rise to 99% yield of the desired product **3ah** in < 1 h (Table 4.3, entry 10) whereas N-benzylidene-4-chloroaniline showed a TOF of 1555 h^{-1} in 98% yield of **3ai** in < 2 h (Table 4.3, entry 11). Under these conditions, but with a comparatively lower loading of 0.02 mol% of **IIIA**, an imine bearing electron rich amine part, N-benzylidene-4-methoxyaniline showed a TOF of 7760 h^{-1} in the first 0.25 h giving rise to a yield of 97% of the desired product **3aj** in < 1 h (Table 4.3, entry 12). N-(4-methoxybenzylidene)-4-chloroaniline showed under these conditions and loadings, a TOF of > 2425 h^{-1} with a yield of 98% of the desired amine **3bi** within 2 h (Table 4.3, entry 13). With the same loading, but at the higher temperature of 120 °C, N-benzylidene-1-naphthylamine was converted with a TOF of > 950 h^{-1} in the first 0.25 giving rise to 95% yield of the desired product **3aj** in < 1 h (Table 4.3, entry 14). Imines bearing aliphatic amine parts, like N-benzylidene-1-hexylamine and N-benzylidene-isobutylamine, gave yields of 95% of the desired amines **3ad** and **3ak,** respectively, in 5 h and 8 h when a catalyst loading of 0.15 mol% of **IIIA** was adopted at a temperature of 120 °C (Table 4.3, entries 15 and 16). Hydrogenation of the ketimine, phenyl-(1-

phenylethylidene)amine furnished under the previous hydrogenation conditions and a loading of 0.5 mol% of **IIIA** a TOF of > 198 h^{-1} and a yield of 98% of the desired N-(1-phenylethyl)aniline product in < 2 h (Table 4.3, entry 17).

4.2.3. Mechanistic Studies and Preparation of $[Re(A)(Br)_3(NO)][NEt_4]$ and formation of $[Re(POP)(Br)_2(NO)]$ (POP = A)

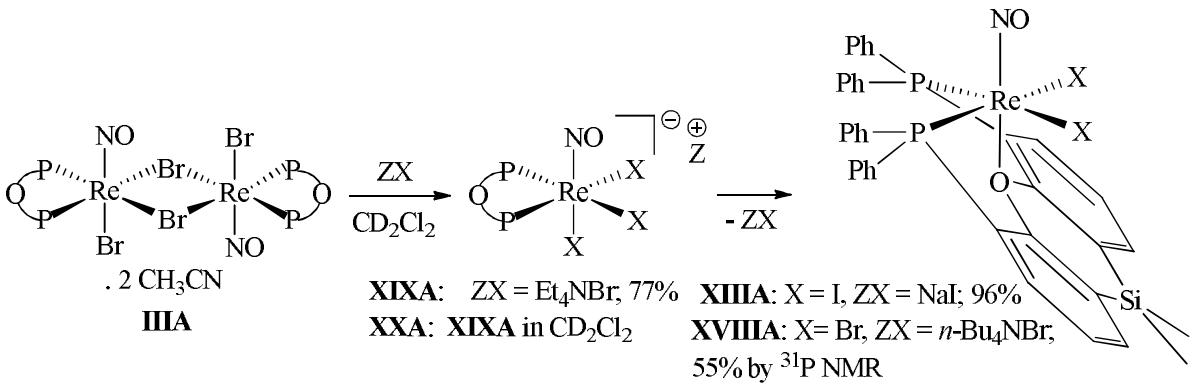
The complex **IIIA** is only sparingly soluble in THF even at a temperature of 90 °C. However, it was found to be more and sufficiently soluble in the presence of 50 equiv. of imine (N-benzylideneaniline). The stoichiometric reaction of complex **IIIA** (which constitutes CH_3CN) with H_2 led to the formation of the [Re]NH_3 complex **XVIA** and the same reaction with benzonitrile and H_2 produced the [Re]benzaldehydeimine complex **XVIIA**. Also, **IIA** or **IIIA** were active in the hydrogenation of styrene in absence of a co-catalyst. From these experiments we concluded that either a bromide ligand or one of the phosphine moieties had dissociated during catalysis (Chapter 3). Applying a 10 mol% loading of **IIIA**, the hydrogenation of the imine, N-benzylideneaniline was attempted under a H_2 pressure of 10 bar and at 90 °C in dichloromethane run for 30 min, which showed complete consumption of the imine. Analysis of the final reaction mixture showed the catalyst **IIIA** and its acetonitrile derivative **IIA** in a ratio of 82:16 according to a ^{31}P NMR spectrum along with traces of other unidentified products. Thus, the formation of **IIA** from **IIIA** can be ruled out as a rate limiting step.

We thought then to first explore whether a mechanism with the possibility of a dissociation of one of the phosphine atoms of the sixantphos ligand could be operative under the catalytic conditions. For this reason, the dibenzofuran monophosphine complex **XIVD** was prepared and applied as a catalyst found to be much less active in the hydrogenation reaction of imines when compared to **IIIA**. Also, though not so promising, the possibility of a protonation of one of the phosphorus arms of the diphosphine ligand occurring in a

bifunctional manner across Re-P bond during catalysis concomitant with its dissociation was examined by addition of 2 or 20 equiv. of DBFphos to this reaction using **XIVD**. However, this did not improve the performance of the catalysis, instead retarded it. From the above experimental observations, one can rule out the possibility of a phosphine dissociation as a crucial step in the catalytic cycle.

The last possibility of a kinetic influence of the ligand on the catalytic reaction course was to check reversible bromide dissociation.[15] The addition of 100 equiv. of *n*-Bu_4NBr with respect to **IIIA** was expected to retard the hydrogenation of N-benzylideneaniline. However, an unprecedented great increase in reaction rate was observed; a TOF of 8122 h^{-1} was obtained in the first 0.25 h completing the reaction in less than 1 h using a loading of 0.02 mol% of **IIIA** at 90 °C (Table 4.3, entry 3). This reaction, when carried out with 50 equiv. of *n*-Bu_4NBr showed a lower activity with a TOF of 4957 h^{-1} in the first 0.25 h (Table 4.3, entry 4). Addition of *n*-Bu_4NBr was also seen to increase the activity in the reductive amination (Table 4.1, entry 10).

When 5 equiv. of *n*-Bu_4NBr were added to **IIIA** in THF-d_8, we observed the formation of a new singlet resonance at -2.3 ppm and this reaction in CD_2Cl_2 heated to 100 °C showed a new signal at 0.3 ppm in the ^{31}P NMR spectrum. This reaction mixture was



Scheme 4.2. Reaction of **IIIA** with halides.

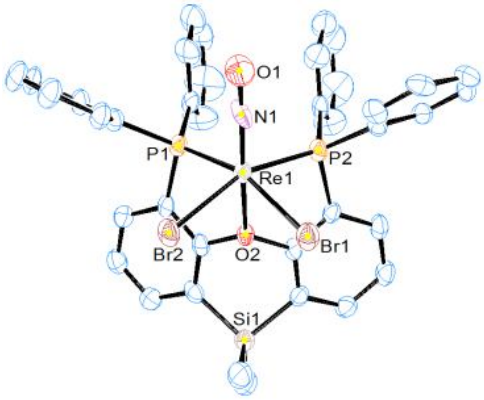


Figure 4.1. Molecular structure of **XVIIIA**. Anisotropic displacement parameters are depicted at the 50% probability level. Hydrogen atoms and solvent molecules are omitted for clarity. Selcected bond lengths: X**VIIIA**: Re1-Br1: 2.580(1); Re1-Br2: 2.5688(9); Re1-O2: 2.196(5); **VIIIA**: Re1-I1: 2.7952(2); Re1-I2: 2.7976(2); Re1-O1: 2.221(2).

evaporated to dryness and extracted with THF. Yellowish brown coloured single crystals could be obtained suitable for X-ray diffraction, along with *n*-Bu_4NBr. The X-ray diffraction analysis showed that the Sixantphos ligand of this compound X**VIIIA** was coordinated in a tridentate fashion with the O atom involved in bonding to the rhenium centre and the two bromides were found disposed *trans* to the phosphorus ligands (Figure 4.1). However, the yield of this reaction to **XVIIIA** in both THF and CH_2Cl_2 did not exceed greater than 55% even when 20 equiv. of *n*-Bu_4NBr was used at 100 °C.

Since complex **XVIIIA** could not be isolated in pure form due to the presence of *n*-Bu_4NBr (chapter 4), we thought to convert **IIIA** to **XVIIIA** using Me_4NBr, which would be easier for purification of **XVIIIA**, but this could not give the product even at a temperature of 100 °C, presumably due to its insolubility in organic solvents. However, when 5 equiv. of Et_4NBr were applied in CD_2Cl_2, 80-85% of the product (^{31}P NMR: 0.1 ppm) was formed analogous to the one obtained with *n*-Bu_4NBr in CD_2Cl_2. This compound when extracted with benzene could give rise to 77% yield of the tribromo anionic complex

[Re(**A**)$(Br)_3(NO)$][NEt_4] (**XIXA)**. Interestingly, though the reaction was incomplete, dispensing **XIXA** in THF showed another peak in ^{31}P NMR spectra with precipitation of Et_4NBr, but this compound was not **XVIIIA**. It is assumed that the THF co-ordinated complex similar to **XVIIIA** had formed. However this reaction could not be enhanced even at a higher temperature of 100 °C. Thus it was concluded that in the reaction of **IIIA** with *n*-Bu_4NBr in CD_2Cl_2 tetra-*n*-butylammonium

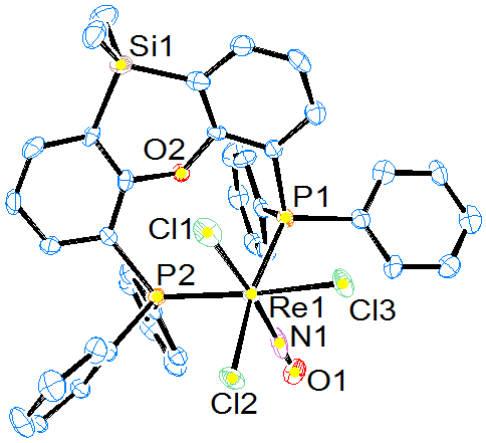


Figure 4.2. Molecular structure of **XXA**. Anisotropic displacement parameters are depicted at the 50% probability level. Et_4N^+, hydrogen atoms and solvent molecules are omitted for clarity.

analogue of **XIXA** was obtained which then transformed completely to **XVIIIA** when dispensed in THF. Interestingly, the isolated complex **XIXA** when dispensed in CD_2Cl_2 showed another peak at 25.9 in the ^{31}P NMR spectra. Single crystals suiable for X-ray diffraction analysis were obtained when benzene was layered on it. This was analyzed to be the trichloroanionic complex [Re(**A**)$(Cl)_3(NO)$][NEt_4] (**XXA**) realizing the participation of dichloromethane in this reaction (Figure 4.2).

However, the formation of complexes **XIIIA** and **XVIIIA** where in these cases the sixantphos O atoms are coordinated *trans* to NO ligand in the presence of halide ions can be explained on the basis of an association-dissociation mechanism (Scheme 4.2). Addition of

halide ions to complex **IIIA** would generate anionic trihalorhenium complexes analogoues to **XIXA** or **XXA** (Scheme 4.2). The observed dissociation of these anionic trihalorhenium complexes in some cases would be due to the increase in electron density on the metal centre, where the push pull interaction in these complexes weakens leading to the dissociation of the halide ligand *trans* to NO ligand and thus totally leaving the halogen salts.

However, a 0.05% loading of the diiodo complex complex **XIIIA** (chapter 2) in the hydrogenation of N-benzylideneaniline at 50 bar H_2 pressure and at a temperature of 90 °C showed a TOF of 2200 h^{-1} in the first 0.25 h giving rise t 97% yield of the desired secondary amine in 3 h (Table 4.3, entry 4). Thus this catalyst was less efficient when compared to **IIIA**. When the dibromo complex **IIIA** (25.3 ppm in ^{31}P NMR) and diiodo complex **XIIIA** (23.1 ppm in ^{31}P NMR) were dispensed in $CDCl_3$ at room temperature, a new signal was also observed at 24.5 ppm in the ^{31}P NMR spectrum, which could be attributed to a rhenium complex bearing a bromide and an iodide ligand. Also, it is worth mentioning that an increase in activity was observed when **IIIA** was used in the catalytic styrene hydrogenation in the presence of catalytic $B(C_6F_6)_3$ when compared to the reaction without $B(C_6F_6)_3$. This was attributed to a capture of the dissociated bromide ion by this boron Lewis acid.[14]

The Hammet correlation was then checked with the series of aryl substituents H, OMe, F and Cl in para position of both the benzylidene part and the amine part of N-benzylideneanilines (Figure 4.3). The plots of log(TOF) *vs* substituent constants (σ) gave slopes (ρ) -2.17 for the substituents on the benzylidene part and -1.41 for those in the amine part.[15] The slopes represents the sensitivity constants, and those greater than unity indicated that the imine hydrogenation is highly sensitive to substituents. Also, a negative value of the ρ indicated a positive charge build up during the reaction.

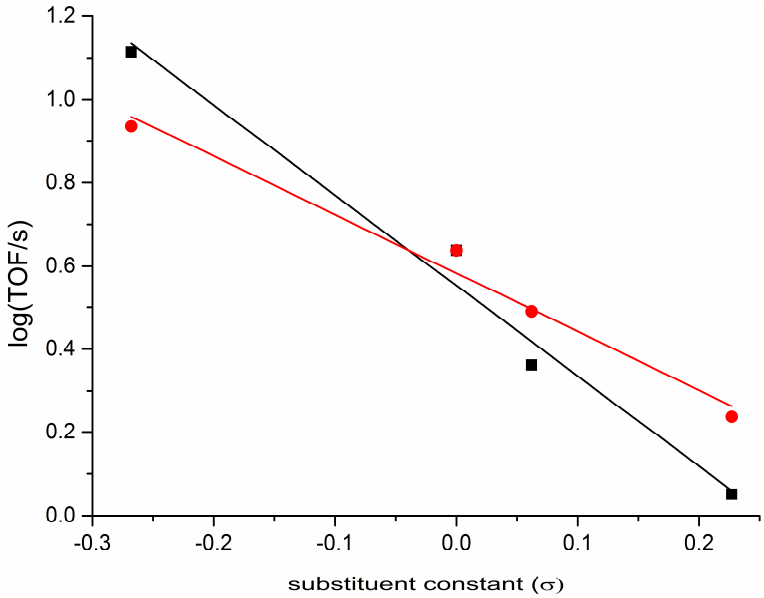
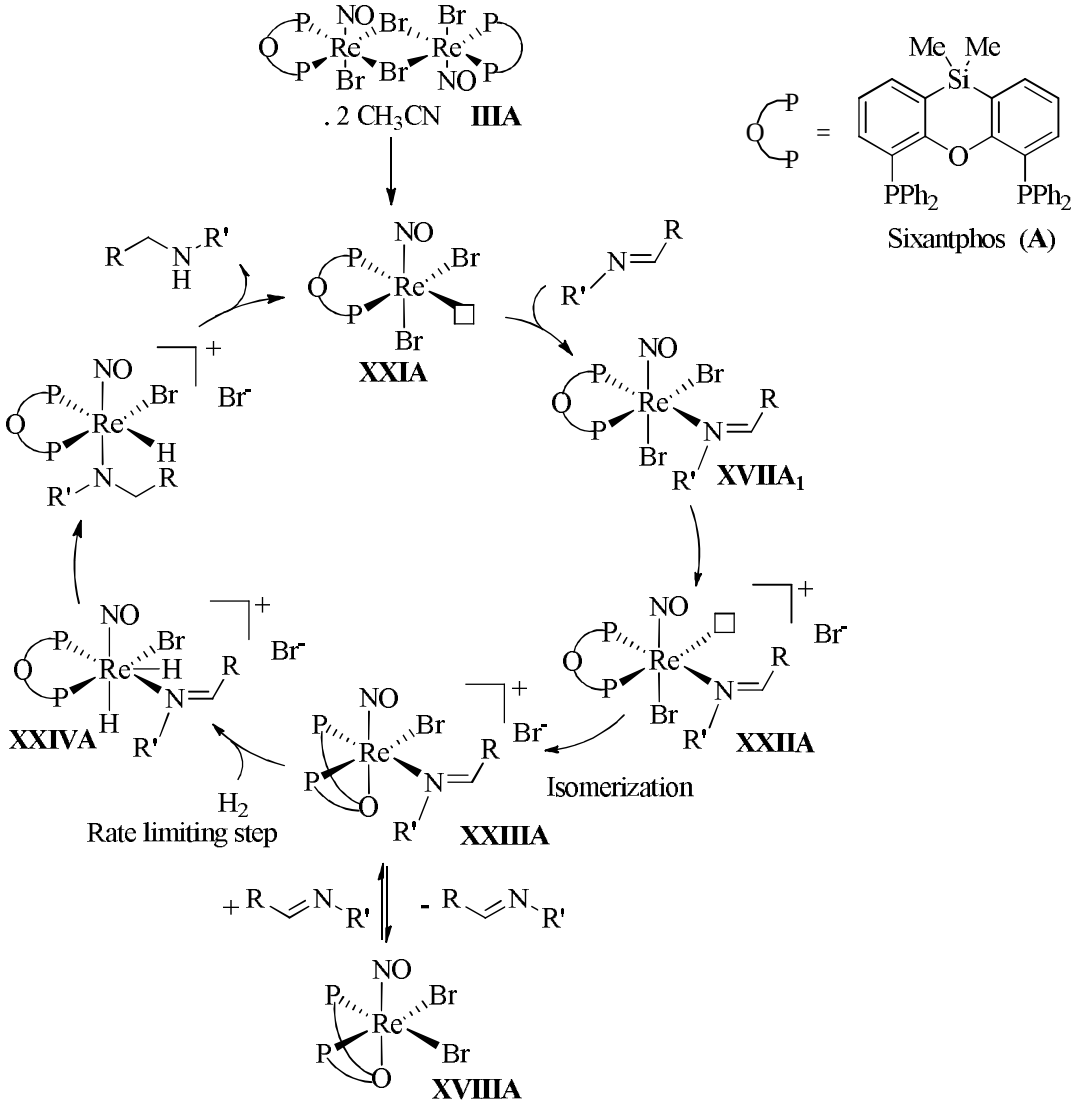


Figure 4.3. Hammet plots of the hydrogenation reactions of N-benzylideneanilines with para substituents using **IIIA**. Black: benzylidene part; left to right: OMe, H, F, Cl. Red: amine part; left to right: OMe, H, F, Cl.

The bromide ligand *trans* to the nitrosyl ligand is comparatively strongly bounded to the rhenium centre due to a strong π push pull interaction in the Br-Re-NO axis. This is revealed in the reactivity of complexes of type **II**, **III**, as well as that of analogous complexes bearing other diphosphine ligands activated with excess triethylsilane and followed by subsequent reaction with ethylene to form complexes **VII,** as well as rhenium complexes bearing a substitution pattern with *cis* disposed ethylene and a H ligands where in all cases the bromide ligand *trans* to NO ligand was not affected (Chapter 2).

The reaction of **IIIA** with N-benzylideneaniline in CH_2Cl_2 at 90 °C furnished partial formation of the C complex **IIA**. This was expected, since acetonitrile is a stronger ligand than the imine. However, under the catalytic conditions, acetonitrile in stoichiometric amounts is either hydrogenated to imines or amines (Chapter 3) or replaced by the imine to be hydrogenated. The ability of such rhenium complexes to hydrogenate nitriles has already been documented.[16] Evidence for imine coordination could be derived from the formation of the benzylideneamine coordinated complex X**VIIA,** when **IIIA** was subjected to H_2 and

benzonitrile at 140 °C (chapter 3). Also, the formation of isomerized imine in the reductive amination reaction of hexanal with 1-hexylamine (Table 4.2, entry 10) indicates coordination of the imine during catalysis and subsequent *β*-hydride abstraction as well known for the classical Wilkinson or Osbon type hydrogenation of olefins by metal hydride catalysts. Thus, a structure **XVIIA$_1$** analogous to **XVIIA** would be formed through the coordinatively unsaturated species **XXIA** under catalytic conditions (Scheme 4.3). Though evidence for this structure **XXIIA** could not be directly drawn from experiments, it is the only possible intermediate at this stage. Both steric and electronic factors arising from the large bite angle



Scheme 4.3. Proposed mechanism for the hydrogenation of imines catalyzed by complex **IIIA**.

Sixantphos ligand would lead to distortion and poor orbital overlap between rhenium and the bound bromide ligand which enhances the dissociation of the bromide ligand *trans* to this diphosphine.[16] The P1Re1P2 angle (bite angle, β) in the complex **IIA** is 97.01(3)° and that in rhenium-imine complex **XVIIA** is 96.19(7)°, indeed prone for a large bite angle effect.

The species $\mathbf{XXIIA_1}$ is assumed to undergo dissociation of the bromide ligand *trans* to the large bite angle diphosphine ligand forming the cationic intermediate **XXIIA**.[14] This species is assumed to undergo an isomerisation reaction leading to the formation of the species **XXIIIA**. This is enhanced by the addition of halide ions in a similar fashion as described in Scheme 4.2, and thus a direct access to **XXIIIA** from **XVIIIA** would take place. The site *trans* to NO ligand, the most active site for a hydride ligand (more hydridic)[17] and there by a fast insertion of polar substrates into the Re-H bond is thus accessible and the oxidative addition of H_2 to **XXIIIA** forming the Re(III) species **XXIVA** seems to be preferred in this ligand position. A deuterium kinetic isotopic effect ($k(H_2)/k(D_2)$) of 2 indicated that the oxidative addition of H_2 to be the possible rate limiting step. The comparatively larger negative slopes of the Hammett plots for substituents on the aldehydic and the amine part, that even much more prominent in the aldehydic part is expected to be due to advancing the rhenium centre more electron rich through the N atom of the imine which would enhance this oxidative addition of dihydrogen. Insertion of the coordinated imine in to the $Re\text{-}H_{trans\ to\ NO}$ bond followed by reductive elimination of the amine would regenerate the species **XXIA**.

4.3. Conclusion

In summary, using rhenium complexes we have developed an efficient homogeneous catalysis for the reductive amination of aldehydes including α,β-unsaturated aldehydes showing excellent selectivities for the production of substituted amines. A highly efficient homogeneous hydrogenation of imines using one of the rhenium(I) complexes was also

discovered. Electron rich aromatics showed comparatively high activities in these processes. Though the reaction was found to be very efficient, electron withdrawing substituents on the aldehydic part were much inferior when compared with these substituents on the amine part. In this context we had also seen the ability of the given rhenium complexes to induce catalytic dehalogenations, as well as hydrogenation of aldehydes including formaldehyde to their corresponding alcohols. A reversible halide ligand dissociation to generate active species followed by a classical mechanism involving oxidative addition of dihydrogen, insertion of amine into the Re-H bond followed by reductive elimination is proposed for this hydrogenation reaction of imines. The ability of this rhenium complexes to hydrogenate ketimines further opens up the opportunity for ligand sphere tuning using appropriate chiral diphosphines thereby to impart highly efficient stereoselective hydrogenations.

4.4. Experimental Section

All manipulations of addition of reaction components and samplings were done in a glove box filled with dry N_2. All the reagents are purchased from either Aldrich or ABCR chemical company and used without further purification.

4.4.1. Preparation of [Re(A)Br$_3$(NO)][NEt$_4$] (XIXA)

Complex **IIIA** (100 mg, 0.099 mmol) and Et_4NBr (104 mg, 0.494 mmol) was taken in a Young Schlenk flask and CH_2Cl_2 (1 mL) was added to it. It was heated to 100 °C for 1 h. The mass was cooled to room temperature, concentrated to dryness. The residue was extracted with benzene (2 x 1 mL), concentrated and dried to get the product **XIXA** as orange solid. Yield: (95 mg, 0.0761 mmol, 77%); IR (KBr, cm^{-1}): 3053 (w), 2980 (w), 2946 (w), 1676 (s), 1482 (w), 1434 (m), 1378 (s), 1247 (w), 1228 (w), 1186 (w), 1095 (w); ^{1}H NMR (500 MHz, C_6D_6): δ 0.30 (s, 3H), 0.32 (s, 3H), 1.85 (t, 12H, *J* = 7.5 Hz), 3.02 (q, 8H, *J* = 7.5 Hz), 6.73-6.78 (m, 8H), 6.98-7.05 (m, 6H), 7.26 (d, 2H, *J* = 7 Hz), 7.30-7.33 (m, 2H), 8.07 (m, 8H); ^{31}P{^{1}H}NMR (121 MHz, $CDCl_3$): δ 0.1 (s); Anal. (%). Calc for $C_{46}H_{52}Br_3N_2O_2P_2ReSi$: C, 46.79; H, 4.44; N, 2.37. Found: C, 47.11; H, 4.57; N, 2.40.

4.4.2. Typical procedure for the direct reductive amination of aldehydes

Catalyst **IIIA** (0.002 g, 1.976 ×10^{-3} mmol) was taken in a stainless steel autoclave. Benzaldehyde (0.419 g,

3.953 mmol) and aniline (0.368 g, 3.953 mmol) were added followed by THF (1.5 mL). The autoclave was pressurized with 50 bar of hydrogen and kept in an oil bath maintained at 90 °C. After appropriate reaction time, the vessel was cooled to room temperature and the hydrogen was slowly released in a fume hood. Solvent was evaporated, redissolved in dichloromethane, filtered through a short plug of $MgSO_4$ and the yield was measured by GC/MS based on the consumption of aniline.

4.4.3. Typical procedure for the hydrogenation of imines

Catalyst **IIIA** (0.002 g, 1.976 $\times 10^{-3}$ mmol) was taken in a stainless steel autoclave. N-benzylideneaniline (1.791 g, 9.881 mmol) was added followed by THF (3 mL). The autoclave was pressurized with 50 bar of hydrogen and kept in an oil bath maintained at 90 °C. After appropriate reaction time, the vessel was cooled to room temperature and the hydrogen was slowly released in a fume hood. The mass was filtered through a short plug of celite and the yield was measured by GC/MS based on the consumption of the imine.

GC/MS data of aldehydes, imines and amines: (MS (CP-3800 Saturn 2000MS/MS spectrometer, Column: Brechbuhler, ZB-5ms, 30m x 0.25mm x 0.25µm) (compound: retention time, mass peak): **1a**: 3.66 min (m/z = 106); **1b**: 6.06 min (m/z = 136); **1c**: 6.79 min (m/z = 151); **1d**: 5.05 min (m/z = 140); **1e**: 8.13 min (m/z = 156); **1f**: 3.93 min (m/z = 112); **1h**: 2.86 min (m/z = 100); **1j**: 4.19 min (m/z = 132); **2a**: 3.75 min (m/z = 93); **2b**: 6.03 min (m/z = 219); **2c**: 8.64 min (m/z = 138); **2d**: 2.74 min (m/z = 101); **2f**: 7.24 min (m/z = 169); **2g**: 1.63 min (m/z = 85); **3aa**: 9.33 min (m/z = 183); **3ab**: 10.28 min (m/z = 309); **3ac**: 13.04 min (m/z = 307); **3ad**: 8.02 min (m/z = 191); **3ae**: 4.02 min (m/z = 107); **3af**: 10.11 min (m/z = 259); **3ag**: 5.70 min (m/z = 175); **3ca**: 13.19 min (m/z = 228); **3da**: 10.71 min (m/z = 217); **3ea**: 13.93 min (m/z = 233); **3fa**: 9.42 min (m/z = 189); **3ga**: 6.15 min (m/z = 149); **3hd**: 6.63 min (m/z = 185); **3ia**: 5.20 min (m/z = 107); **3if**: 7.25 min (m/z = 183); **3ja**: 11.30 min (m/z = 209); **3ka**: 13.04 min (m/z = 228); **3la**: 9.43 min (m/z = 201); **3ma**: 9.43 min (m/z = 197); **3ai**: 10.84 min (m/z = 217); **3bi**: 13.70 min (m/z = 233); **3ak**: 6.10 min (m/z = 149); **5aa**: 9.07 min (m/z = 181); **5ab**: 9.96 min (m/z = 307); **5ba**: 10.29 min (m/z = 215); **5ac**: 12.11 min (m/z = 226); **5da**: 10.29 min (m/z = 215); **5ea**: 13.74 min (m/z = 257); **5fa**: 9.07 min (m/z = 187); **5ga**: 9.07 min (m/z = 147); **5ad**: 7.95 min (m/z = 189); **5hd**: 6.30 min (m/z = 183); **5ae**: 9.07 min (m/z = 181); **5ia**: 9.07 min (m/z = 181); **5ja**: 10.63 min (m/z = 207); **5ka**: 12.11 min (m/z = 226); **5la**: 9.04 min (m/z = 199); **5ai**: 10.37 min (m/z = 215); **5bi**: 12.56 min (m/z = 245); **5aj**: 13.30 min (m/z = 231); **5ad**: 7.92 min (m/z = 189); **5ak**: 6.06 min (m/z = 147); **5ma**: 8.86 min (m/z = 195); **9hd**: 7.00 min (m/z = 183); **10hd**: 9.60 min (m/z = 265); **11a**: 4.19 min (m/z = 106); **11b**: 6.15 min (m/z = 138); **11d**: 5.90 min (m/z = 142); **11e**: 8.58 min (m/z = 158); **11f**: 4.23 min (m/z = 114); **11h**: 2.82 min (m/z = 102); **11j**: 6.42 min (m/z = 136).

4.5. References

1 a) S. Gomez, J. A. Peters, T. Maschmeyer, *Adv. Synth. Catal.* 2002, *344*, 1037-1057; b) B. Chen, U. Dingerdissen, J. G. E. Krauter, H. G. J. L. Rotgerink, K . Mobus, D. J. Ostgard, P. Panster, T. H. Riermeier, S. Seebald, T. Tacke, H. Trauthwein, *Appl. Catal. A: Gen.* 2005, *280*, 17-46; A. Galan, J. de Mendoza, P. Prados, J. Rojo A. M. Echavarren, *J. Org. Chem.* 1991, *56*, 452-454. a) R. N. Salvatore, C. H. Yoon, K. W. Jung, *Tetrahedron*, 2001, *57*, 7785-7811; and see reference therein; b) M. Freifelder, *Catalytic Hydrogenation in Organic Synthesis: Procedures and Commentary*; (Wiley: New York, 1978; Chapter 10). a) B. Miriyala, S. Bhattacharyya, J. S. Williamson, Tetrahedron, 2004, *60*, 1463-1471; b) A. Togni, L. M. Venanzi, *Angew. Chem. Int. Ed.* 1994, *33*, 497-526; c) M. Sawamura, Y. Ito, *Chem. Rev.* 1982, *92*, 857-871.

2. For reviews and recent examples; see, a) A. F. Abdel-Magid, S. J. Mehrman, *Org. Process Res. Dev.* **2006**, *10*, 971-1031 b) M. Tajbakhsh, H. Alinejad, M. Azarpira, M. Hosseinzadeh, H. Sadeghifara, S. Khaksar, *Iran. J. Org. Chem.* **2009**, *2*, 88-91; c) M. Tajbakhsh, R. Hosseinzadeh, H Alinezhad, S. Ghahari, A.Heydari, S. Khaksar, *Synthesis* **2011**, *3*, 490-496; J. Han, V. Tschernutter, J. Yang, T. Eckle, C. H. Borchers, *Anal. Chem.* **2013**, *85*, 5965-5973; d) R. Lokhande, J. Sonawane, A. Roy, L. Ravishankar, *Green Chem. Lett. Rev.* **2011**, *4*, 69-72; e) P. V. Ramachandran, P. D. Gagare, K. Sakavuyia, P. Clark, *Tetrahedron Lett.* **2010**, *51*, 3167-3169; f) J. E. Grob, J. Nunez, M. A. Dechantsreiter, L. G. Hamann, *J. Org. Chem.* **2011**, *76*, 4930-4940 g) O. Y.Wong, A. E. Mulcrone, S. K. Silverman, *Angew. Chem. Int. Ed.* **2011**, *50*, 11679-11684; h) N. U. Kumar, B. S. Reddy, V. P. Reddy, R. Bandichhor , *Tetrahedron Lett.* **2012**, *53*, 4354-4356; i) G. A. Molander, D. J. Cooper, *J. Org. Chem.* **2008**, *73*, 3885-3891; k) F. I. McGonagle, D. S. MacMillan, J. Murray, H. F. Sneddon, C. Jamiesona, A. J. B. Watson, *Green Chem.* **2013**, *15*, 1159; l) J. Nöth, K. J. Frankowski, B. Neuenswander, J. Aubé, O. Reiser, *J. Comb. Chem.* **2008,** *10*, 456-459; m) R. Neelarapu, P.A. Petukhov, *Tetrahedron* **2012**, *68*, 7056-7062. n) H. Firouzabadia, N. Iranpoora, H. Alinezhad, *J. Iran. Chem. Soc.* **2009**, *6*, 177-186; o) E. E. Boros, J. B. Thompson, S. R. Katamreddy, A. J. Carpenter, *J. Org. Chem.* **2009**, *74*, 3587-3590; p) H. Alinezhad, M. Tajbakhsh, F. Salehian, K. Fazli, *Tetrahedron Lett.* **2009**, *50*, 659-661; q) E. M. Dangerfield, C. H. Plunkett, A. L. Win-Mason, B. L. Stocker, M. S. M. Timmer, *J. Org. Chem.* **2010**, *75*, 5470-5477; r) Md. W. Ahmad, S. Y. Lee, T. J. Kim, H-S Kim, *Bull. Korean Chem. Soc.* **2011**, *32*, 4079-4082; s) S. Chandrasekhar, V. M. Rao, *Tetrahedron: Asymmetry* **2012**, *23*, 1005-1009; t) W. Liao, Y. Chen, Y. Liu, H. Duan, J. L. Petersen, X. Shi, *Chem. Commun.*, **2009**, 6436-6438.

3. a) T. Mizuta, S. Sakaguchi, Y. Ishii *J. Org. Chem.* **2005**, *70*, 2195-2199; b) R.-Y Lai, C.-I Lee, S.-T Liu, Tetrahedron **2008**, *64* 1213-1217; c) R. Apodaca, W. Xiao, *Org. Lett.* **2001**, *3*, 1745. d) O.-Y Lee, K.-L Law, D. Yang, *Org. Lett.* **2009**, *11*, 302-3305. e) O. -Y Lee, K-L Law, C.-Y Ho, D. Yang, *J. Org. Chem.* **2008**, *73*, 8829-8837; f) P. D. Pham, P. Bertus, S. Legoupy, *J. Chem. Soc., Chem. Commun.* **2009**, 6207-6209; g) S. C. A. Sousaa, A. C. Fernandes, *Adv. Synth. Catal.* **2010**, *352*, 2218-2226; h) B. G. Das, P. Ghorai, *Chem. Commun.* **2012**, *48*, 8276-8278; i) B. G. Das, P. Ghorai, **2012**, *48*, 8276-8278; j) S. Enthaler, *Catal. Lett.* **2011**, *141*, 55-61.

4. F.-M. Gautier, S. Jones, X. L*a*, S. J. Martin, *Org. Biomol. Chem.*, **201**1, *9*, 7860-7868.

5. a) B.-C. Chen, J. E. Sundeen, P. Guo, M. S. Bednarz, R. Zhao, *Tetrahedron Lett.* **2001**, *42*, 1245-1246.

6. a) T. Suwa, E. Sugiyama, I. Shibata, A. Baba, *Synlett* **2000**, 556-558; b) I. Shibata, T. Moriuchi-Kawakami, D. Tanizawa, T. Suwa, E. Sugiyama, H. Matsuda, A. Baba, *J. Org. Chem.* **1998**, *63*, 383-385; c) I. Shibata, T. Suwa, E. Sugiyama, A. Baba, *Synlett* **1998**, 1081-1082; d) T. Suwa, I. Shibata, K. Nishino, A. Baba, *Org. Lett*. **1999**, *1*, 1579; e) T. Suwa, E. Sugiyama, I. Shibata, A. Baba, *Synthesis* **2000**, 789-800.
7. a) I. V. Micovic, M. D. Ivanovic, D. M. Piatak, V. D. Bojic, *Synthesis* **199**1, 1043-1045. b) A. da S. Renato, I. H. S. Estevamb, L. W. Biebera *Tetrahedron Lett.* **2007**, *48*, 7680-7682; c) K. Ushikoshi, K. Mori, T. Watanabe, M. Takeuchi, M. Saito, M. *Stud. Surf. Sci. Catal*. **1998**, 114, 357; d) M. Saito, *Catal. Surv. Jpn*. **1998**, 175; e) L. C. Grabow, M. Mavrikakis, *ACS Catal*. **2011**, *1*, 365.
8. a) B. Basu, S. Jha, M. M. H. Bhuiyan, P. Das *Synlett* **2003**, *4*, 555-557; b) N. A. Strotman, C. A. Baxter, K. M. J. Brands, E. Cleator, S. W. Krska, R. A. Reamer, D. J. Wallace, T. J. Wright, *J. Am. Chem. Soc*.**2011**, *133*, 8362-8371; c) Q. Lei, Y. Wei, D. Talwar, C.Wang, D. Xue, J. Xiao, *Chem. Eur. J*. **2013**, *19*, 4021-4029.
9. a) T. Itoh, K. Nagata, A. Kurihara, M. Miyazaki A. Ohsawa, *Tetrahedron Lett.* **2002**, *43*, 3105-3108; b) D. Menche, J. Hassfeld, J. Li, G. Menche, A. Ritter, S. Rudolph, Org. Lett., **2006**, *8*, 741-744; c) M. Zhang, H. Yang, Y. Zhang, C. Zhu, W. Li, Y. Cheng, H. Hua; *Chem. Commun.*, 2011, *47*, 6605–6607; d) V. N. Wakchaure, M. Nicoletti, L. Ratjen, B. List, *Synlett* **2010**, *18*, 2708-2710; e) V. N. Wakchaure, J. Zhou, S. Hoffmann, B. List, *Angew. Chem. Int. Ed.* **2010**, *49*, 4612-4614; f) R. I. Storer, D. E. Carrera, Y. Ni, D. W. C. MacMillan, J. Am. Chem. Soc. **2006**, *128*, 84-86; g) Q. P. B. Nguyen, T. H. Kim, *Synthesis*, 2012, *44*, 1977–1982; h) Q. P. B. Nguyen, T. H. Kim, *Tetrahedron* **2013**, *69*, 4938-4943.
10. K. Saito, T. Akiyama, *Chem. Commun*., **2012**, *48*, 4573–4575.
11. a) A. Robichaud, A. N. Ajjou, *Tetrahedron Lett*. **2006**, *47*, 3633–3636; b) M. D. Bhor, M. J. Bhanushali, N. S. Nandurkar, B. M. Bhanage, *Tetrahedron Lett.* **2008**, *49*, 965–969.
12. a) M. H. S. A. Hamid, P. A. Slatford, J. M. J. Williams, *Adv. Synth. Catal*. **2007**, *349*, 1555-1575; b) R. N. Salvatore, C. H. Yoon and K. W. Jung, *Tetrahedron* **2001**, *57*, 7785; and see reference there in; c) M. Freifelder, in *Catalytic Hydrogenation in Organic Synthesis: Procedures and Commentary*; Wiley, New York, **1978**; Ch. 10.
13. a) V. I. Tararov, R. Kadyrov, T. H. Riermeier, A. Börner, *Chem. Commun.* **2000**, 1867–1868; b) J. G. de Vries, C. J. Elsevier, *Handbook of Homogeneous Hydrogenation, Vol. 1*; (Wiley, Weinheim, **2007**; Chapter 15, pp 437-439); c) K.S. Hayes, *Appl. Catal. A: Gen*. **2001**, *221*, 187-195; d) L. L. Mark′o, J. Bakos, *J. Organomet. Chem.* **1974**, *81*, 411-414; e) H -U. Blaser, H -P. Buser, H-P. Jalett, B. Pugina, F. Spindler, *Synlett* **1999**, 867–868; f) T. C. Nugent, M. El-Shasly, *Adv. Synth. Catal*. **2010**, *352*, 753-819; g) J. F. Kniffon, *Catal. Today* **1997**, *36*, 305; h) T. Gross, A. M. Seayad, M. Ahmad, M. Beller, *Org. Lett.* **2002**, *12*, 2055-2058; i) S. Werkmeister, K. Junge, M. Beller, *Green Chem*., **2012**, *14*, 2371-2374; j) A. Pagnoux-Ozherelyeva, N. Pannetier, M. D. Mbaye, S. Gaillard, J- L Renaud, *Angew. Chem. Int. Ed*. **2012**, *51*, 4976-4980; k) S. Fleischer, S. Zhou, K. Junge, M. Beller, *Chem. Asian J*, **2011**, *6*, 2240-2245: l) B. Villa-Marcos, C. Li, K. R. Mulholland, P. J. Hogan, J. Xiao, *Molecules* **2010**, *15*, 2453-2472; m) C. Li, B. Villa-Marcos, and J. Xiao, *J. Am. Chem. Soc*. **2009**, *131*, 6967-6969; n) Y. Chi, Y -Gui Zhou, X. Zhang, *J. Org. Chem.* **2003**, *68*, 4120-4122; o) L. Rubio-Pe´rez, F. J. Pe´rez-Flores, P. Sharma, L. Velasco, A. Cabrera, Org. Lett., **2009**, *11*, 265-268; p) V. I. Tararov, R. Kadyrov, T. H. Riermeier, A. Börner, *Adv.*

Synth. Catal. **2002**, *344*, 200-208; q) G. F. Busscher, L. Lefort, J. G. O. Cremers, M. Mottinelli, R. W. Wiertz, B. de Lange, Y. Okamura, Y. Yusa, K. Matsumura, H. Shimizu, J. G. de Vries, A. H. M. de Vries, *Tetrahedron*: *Asymmetry* **2010**, *21*, 1709-1714; r) O. Bondarev, C. Bruneau, *Tetrahedron*: *Asymmetry* **2010**, *21*, 1350-1354.

14. Y. Jiang, J. Hess, T. Fox, H. Berke, *J. Am. Chem. Soc*. **2010**, *133*, 18233-18247.
15. L. P. Hammet, *J. Am. Chem. Soc*. **1937**, *59*, 96-103.
16. a) K. A. Lenero, M. Kranenburg, Y. Guari, P. C. J. Kamer, P. W. N. M. van Leeuwen, S. Sabo-Etienne, B. Chaudret, Inorg. Chem. 2003, 42, 2859-2866; b) P. C. J. Kamer, P. W. N. M. Van Leeuwen, J. N. H. Reek, *Acc. Chem. Res.* **2001**, *34*, 895-904.
17. a) R. R. Schrock, J. A. Osborn, *J. Am. Chem. Soc.* **1976**, *98*, 2134; b) R. R. Schrock, J. A. Osborn, *J. Am. Chem. Soc*. **1976**, *98*, 4450; c) R. H. Crabtree, A. Gautier, G. Giordano, and T. Khan, *J. Organometal. Chem*. **1977**, *141*, 113; d) H. Berke, P. Burger, *Comments Inorg.Chem*. **1994**, *16*, 279-312; e) H. Jacobsen, H. Berke, in *Recent Advances in Hydride Chemistry*; (Ed.: R. Poli), Elsevier: Amsterdam, Holland, **2001**; pp 89-116; f) A. Choualeb, E. Maccaroni, O. Blacque, H. W. Schmalle, H. Berke, *Organometallics* **2008**, *27*, 3474-3481.

Homogeneous Hydrogenation/Hydrosilylation of Carbon Dioxide to Methanol Catalyzed by Rhenium Complexes

5.1. Introduction

The inexpensive, abundant, of low toxicity CO_2 gas is one of the main originators for green house effect and thereby leading to global warming and climatic changes.[1] The burning of fossil fuels to serve the world's energy demands has led to accumulation of this gas in the atmosphere.[2] The future energy demand relies on sustainable or renewable energy sources, since it is estimated that the fossil fuel sources will deplete in the near future.[3] In this context, production of synthetic fuel from environmentally harmful carbon sources would be a method of choice. For that reason the hydrogenation of carbon dioxide to methanol, a C_1 feed stock, is highly demanded to run the daily needs of the future, thereby to recycle CO_2 and to reduce CO_2 emissions.[4]

Hydrogenation of CO_2 to methanol has been reported with heterogeneous catalytic systems. Most prominent among them are the Cu-Zn based systems that operate at relatively high temperatures and pressures.[5] These processes limit the advantages of tuning the catalytic systems to be operateed at ambient conditions with high efficiency and selectivity. On the other hand, the homogeneous catalytic systems offer opportunity for ligand sphere turning thereby imparting it to be operational at ambient conditions and with excellent selectivities.[6] Remarkable achievements in industrial processes have evoked from the concept of homogeneous transition metal catalysis, but they are dominated by scarce precious metals, like Ru, Rh, Pd and Ir.[7] In the recent past, tremendous efforts were made in academic

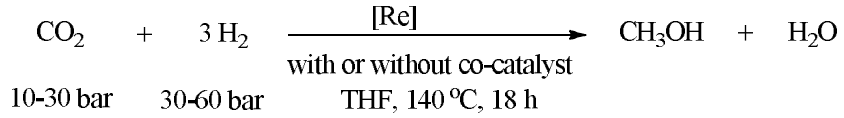
research to develop catalytic systems that are capable of reducing CO_2 to formates using well defined Ru, Rh and Ir systems.[8] Efficient hydrogenations of formate esters and organic carbonates to methanol were realized using Milstein's pincer type ruthenium catalysts.[9] Reduction of CO_2 to methanol has been achieved using boranes, phosphaboranes and silanes, but apart from the issue of high costs, these reagents lead also to the formation of large amount of waste.[10] Preliminary outcome of the efforts on metal catalyzed homogeneous reduction of CO_2 to methanol was reported recently by Huff and Sanford through ruthenium catalyzed cascade reaction involving formic acid and methyl formate as intermediates.[11] In this report, different ruthenium complexes, which are reported to be capable of catalyzing CO_2 to the formate level, and formate esters to methanol were rationally sequenced along with the presence of an acid co-catalyst, the latter was added to enhance esterification and all carried out in a single reaction vessel to effect this transformation. Quite recently, Leitner and co-workers demonstrated this reaction using a ruthenium-phosphine catalytic system, which was already found to be efficient for the hydrogenation of carboxylic acids and their derivatives to the corresponding alcohols.[12] In either of these cases, suitable additives were necessary to perform these reactions. Also, all these catalytic systems were to be handled under air and moisture free conditions.

5.2. Results and Discussion

5.2.2. Catalytic Hydrogenation of Carbon Dioxide to Methanol

In the recent past, our group has developed highly efficient homogeneous rhenium based hydrogenation catalysts, some of which showed activities comparable to those of precious metals in hydrogenations of olefins. CO_2 reduction assisted by rhenium hydride/$B(C_6F_6)_3$ 'Frustrated Lewis Pair' has been recently documented as well.[14] Based on the diphosphine nitrosyl rhenium complexes discussed in the previous chapters, we describe

Table 5. 1. Hydrogenation of carbon dioxide to methanol catalyzed by various rhenium complexes[a]



Entry	[Re]	Co-catalyst 1 /Equiv.	Co-catalyst 2 /Equiv.	CO_2/H_2 (bar)	TON[b]
1	**IIIA**	-	-	10/30	07
2	**IIIA**	*n*-Bu_4NBr /5	-	10/30	28
3	**IIIA**	*n*-Bu_4NBr /5	-	10/30	26[c]
4	**XIXA**	-	-	10/30	07
5	**XIXA**	-	-	10/30	00[d]
6	**XIXA**	-	-	10/30	00[e]
7	**XIIIA**	-	-	10/30	13
8	**IIIA**	*n*-Bu_4NI /100	-	10/30	11
9	**IIIA**	NaI/100	-	10/30	05
10	**IIIA**	*n*-Bu_4NBr /2	-	10/30	20
11	**IIIA**	*n*-Bu_4NBr /50	-	10/30	30
12	**IIIA**	*n*-Bu_4NBr /100	-	10/30	30
13	**IIIA**	Et_4NBr /100	-	10/30	1.6
14	**XIIIA**	*n*-Bu_4NBr /100	-	10/30	33
15	**IIIA**	*n*-Bu_4NBr /5	-	10/30	0.9[f]
16	**IIIA**	-	EtOH/250	10/30	06
17	**IIIA**	*n*-Bu_4NBr /100	EtOH/250	10/30	33
18	**IIIA**	*n*-Bu_4NBr /5	EtOH/100	10/30	29[g]
19	**XXVA**	-	-	10/30	20
20	**IIIA**	-	-	20/60	12
21	**IIIA**	*n*-Bu_4NBr /5	-	20/60	88
22	**XIVD**	-	-	10/30	00

[a]0.005 mmol of catalyst, 1 mL of solvent, TON by ^1H NMR spectroscopy using DMF as internal standard; [b]moles of MeOH/moles of Re; [c]Reaction components were charged in open air. [d]H_2O as solvent; [e]Toluene as solvent; [f]1:1 mixture of H_2O:THF as solvent; [g]5 equiv. of *p*-TsOH;

herein the production of methanol via homogeneous hydrogenation and hydrosilylation of CO_2. Initial testing and optimization of the hydrogenation reaction using rhenium complexes were carried out at a CO_2 pressure of 10 bar and a H_2 pressure of 30 bar at 140 °C in THF run for 18 h (Table 5.1). The rhenium complex **IIIA** alone under these conditions gave methanol with a TON of 7 quantified by ^{1}H NMR spectroscopy using DMF as an internal standard (Table 5.1, entry 1). The formation of methanol is further confirmed by ^{31}C NMR spectroscopy and again by adding a little of methanol to this mixture followed by further analysis. Since the activity of this complex in hydrogenations was found to increase by the addition of *n*-Bu_4NBr and due to the formation of complex **XVIIIA** (Chapter 4), we added 5 equiv. of *n*-Bu_4NBr with respect to the catalyst and performed the hydrogenation of CO_2. We could achieve a TON of 28 under the above mentioned conditions of optimization (Table 5.1, entry 2). It is worth mentioning that the starting components of this reaction could be handled in open air, which gave comparable results with those reactions handled in a glove box (Table 5.1, entry 3). The tribromo anionic complex **XIXA** as a catalyst gave only a TON of 7 under the above hydrogenation conditions (Table 5.1, entry 4). It is worth mentioning that the complex **XIXA** could not give any product when the reaction was carried out in water or toluene (Table 5.1, entries 5 and 6). The diiodo complex **XIIIA** was found to produce methanol with a TON of 13 under the above hydrogenation conditions whereas **IIIA** with presence of 100 equiv. of *n*-Bu_4NI with respect to **IIIA** allowed TON of 11 (Table 5.1, entries 7 and 8). However, complex **IIIA** along with 100 equiv. of NaI in THF provided a TON of only 5 (Table 5.1, entry 9). Addition of only 2 equiv. of *n*-Bu_4NBr along with **IIIA** could give a TON of 20, which is a little less in quantity of methanol when compared to the reaction with 5 equiv (Table 5.1, entry 10). However, addition of 50 or even 100 equiv. of *n*-Bu_4NBr to this reaction gave TONs comparable to the reaction that with 5 equiv. (Table 5.1, entries 11 and 12). From these observations, it was concluded that the role of *n*-Bu_4NBr that

under catalytic conditions was to convert complex **IIIA** to **XVIIIA** under the. However, the reaction using **IIIA** along with 100 equiv. of Et_4NBr was seen to give methanol in a TON of only 1.6 (Table 5.1, entry 13). This reduced activity is anticipated to be due to the increased formation of complex **XIXA** which is inactive in catalysis unless it dissociates bromide (as Et_4NBr) in THF as discussed in Chapter 5. Addition of 5 equiv. of *n*-Bu_4NBr along with **XIIIA** provided the higher TON of 33 (Table 5.1, entry 14). A reaction in a 1 : 1 mixture of H_2O : THF was seen to provide a TON of only 0.9 (Table 5.1, entry 15), for reasons which cannot be explained as yet.

In order to enhance the formation of the first reduced product, formic acid, by stabilizing it as formate ester, 250 equiv. of ethanol was added to the reaction mixture using **IIIA** as catalyst and no other additive. However, this did not lead to an improved TON (Table 5.1, entry 16). Also, this reaction of addition of ethanol in the presence of *n*-Bu_4NBr did not show any significant improvement when compared to the reaction without the addition of ethanol (Table 5.1, compare entries 12 and 17). The hydrogenation reaction in the presence of 100 equiv. of ethanol and 5 equiv. of *p*-TsOH to enhance the ester formation also could not provide any significant increase in TON (Table 5.1, entry 18). Also, ethyl formate or methyl formate could not be observed in ^1H NMR spectra, even not in traces.

Now, on attempts to synthesize a Re-formate complex, **IIIA** was reacted with with 5 equiv. of sodium formate in acetone (laboratory grade) at 55 °C. This revealed a dinuclear trihydroxy complex $[Re_2(A)_2\mu^3\text{-}(OH)_3(NO)_2][Br]$ (**XXVA**) (Figure 5.1). However, this complex could not be obtained when dry acetone was used, instead the formation of various other species were observed which require further characterization. Quite surprisingly, the μ-hydroxy compound **XXVA** could not be obtained when water or NaOH was reacted instead of sodium formate. However, according to ^{31}P NMR spectrum the formation of other

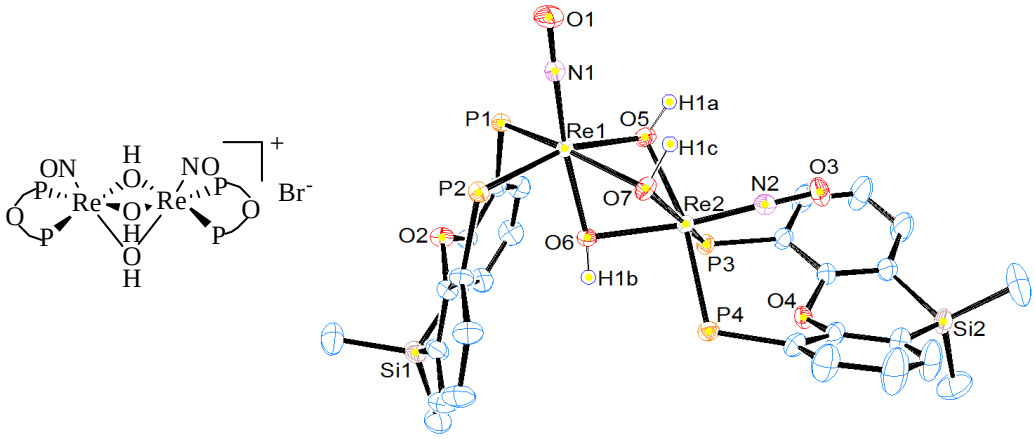


Figure 5.1. Complex **XXVA** (left) and Molecular structure of it (right). Anisotropic displacement parameters are depicted at the 50% probability level. Ph groups on P atoms, Br^-, hydrogen atoms except those on bridging O and solvent molecules are omitted for clarity.

unidentified species was prevailing. Thus, at this stage, we conclude that water led to formation of product **XXVA** from **IIIA**. In hydrogenation experiments to yield methanol, **XXVA** as a catalyst provided a TON of 20 under the above mentioned reaction conditions (Table 5.1, entry 19).

Tuning the methanol production under relatively mild conditions, further we thought to carry out these reactions under pressures of 20 bar CO_2 and 60 bar H_2 at the temperature of 140 °C and run for 18 h. The reaction using **IIIA** as a catalyst gave methanol with TON of 12 (Table 5.1, entry 20). Another run of this reaction along with 5 equiv. of *n*-Bu_4NBr furnished methanol with a TON of 88 (Table 5.1, entry 21). However, the same reaction conditions using the monophosphine complex **XIVD** did not show hydrogenation of CO_2 (Table 5.1, entry 22), which emphasized the necessity for large bite angle diphosphines in the coordination sphere of rhenium.

5.2.2. Hydrosilylation and Combined Hydrogenation/Hydrosilylation of Carbon Dioxide to Methanol Using Complexes IIIA and XVIIA.

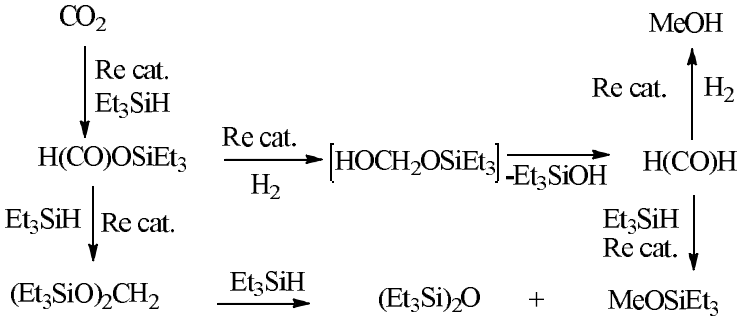
Based on our previous studies to improve the activity of rhenium Sixantphos nitrosyl

complexes including **IIIA** along with Et_3SiH as a co-catalyst for the hydrogenation of olefins (Chapter 2) and nitriles (Chapter 3), we thought to apply this strategy for this hydrogenation of CO_2 to methanol. Complex **IIIA** along with 25 equiv. of Et_3SiH furnished under the conditions of 10 bar CO_2 and 30 bar H_2 in THF run for 18 h MeOH in a TON of 16 when quenched in D_2O. This reaction with the addition of 5 equiv. of *n*-Bu_4NBr furnished methanol in a TON of 51 (Table 5.2, entries 1 and 2). In these cases of catalysis, both hydrogenation and hydrosilylation reactions are combined to faster the formation of methanol (Scheme 5.1). A run of this reaction using 100 equiv. of Et_3SiH was carried out along with 5 equiv. of *n*-Bu_4NBr showed production of methanol with a TON of 37 and $MeOSiEt_3$ with a TON of 27 when samples were taken in a glove box and analyzed by ^1H NMR spectroscopy using dry

Table 5.2. Hydrosilylation/hydrogenation of carbon dioxide to the methanol level catalyzed by complex **IIIA** and **XIIIA** along with Et_3SiH[a]

Entry	[Re]	Co-catalyst/Equiv.	Et_3SiH (Equiv.)	CO_2/H_2 (bar)	TON[b]
1	**IIIA**	-	25	10/30	16
2	**IIIA**	*n*-Bu_4NBr /5	25	10/30	51
3	**IIIA**	*n*-Bu_4NBr /5	100	10/30	64[c]
4	**IIIA**	*n*-Bu_4NBr /5	100	20/60	130
5	**IIIA**	*n*-Bu_4NBr /5	100	20/60	330[d]
6	**XIIIA**	*n*-Bu_4NBr /5	100	20/60	92
7	**IIIA**	-	40	02/0	3.2
8	**IIIA**	*n*-Bu_4NBr /5	1000	10/0	160
9	**IIIA**	*n*-Bu_4NBr /5	1000	20/0	420[e]

[a]0.005 mmol of catalyst and 1 mL of THF at 140 °C run for 18 h; for entry 7, reaction was carried out at 80 °C and run for 10 h, TON by ^1H NMR spectroscopy sing DMF or mesitylene as internal standard; [b]MeOH: 37; $MeOSiEt_3$: 27. [d]Reaction was run for 96 h. [e]2 equiv. of $B(C_6F_6)_3$ with respect to the catalyst was added.



Scheme 5.1. Reaction pathways in the hydrogenation/hydrosilylation of CO_2 using **IIIA**.

THF-d_8. This reaction mixture when quenched with D_2O followed by ^1H NMR analysis showed methanol with a TON of 64 (Table 5.2, entry 3). A batch of this reaction along with 100 equiv. of Et_3SiH at pressures of 20 bar of CO_2 and 60 bar of H_2 was seen to give methanol in a TON of 130 (Table 5.2, entry 4). Another run of this reaction for 96 h produced methanol with a TON of 330 indicating longevity of the active species (Table 5.2, entry 5). However, this reaction using complex **XIIIA** could give a TON of only 92 in 18 h (Table 5.2, entry 6).

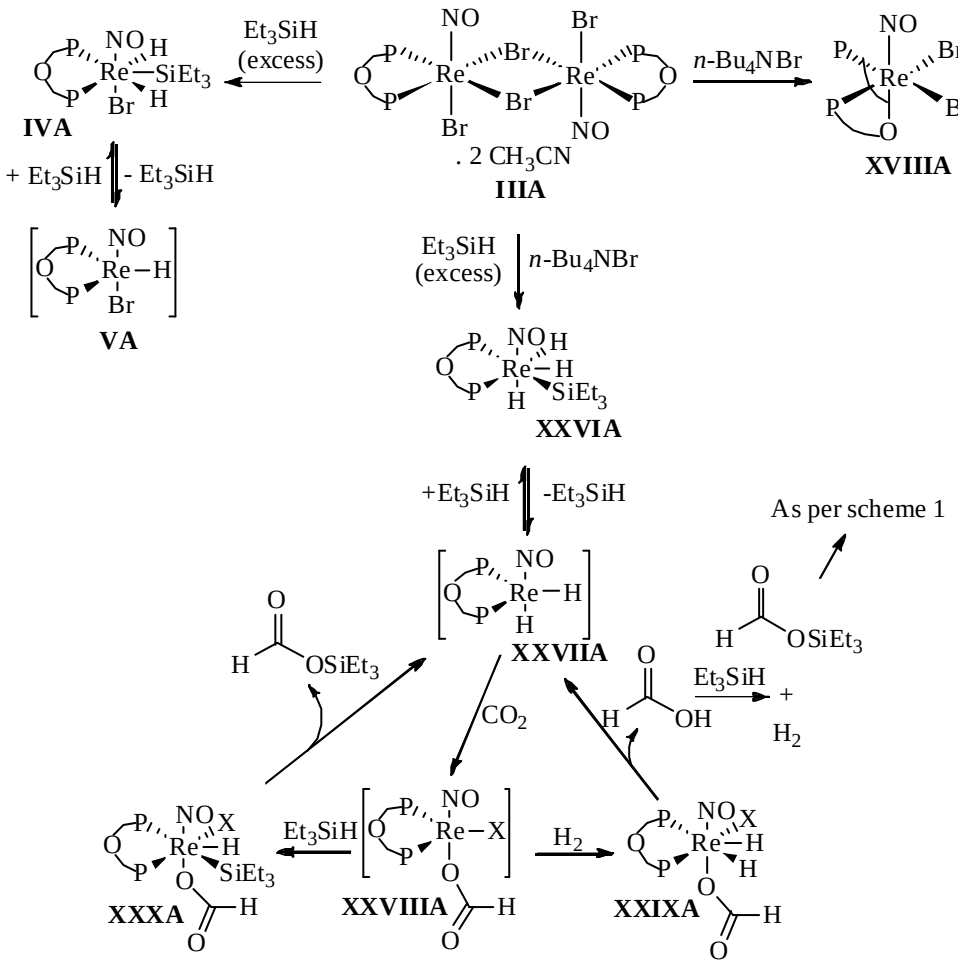
An experiment in a Young NMR tube consisting of 0.005 mmol of **IIIA** along with 50 equiv. of Et_3SiH in THF-d_8 was charged with 2 bar CO_2 revealing the formation of $H(CO)OSiEt_3$ and $MeOSiEt_3$ with TONs of 0.90 and 0.74, respectively, when heated to 80 °C for 1 h. Continuing this reaction for 10 h gave these products in TONs of 0.36 and 3.22 respectively along with traces of $CH_2(OSiEt_3)_2$ (Table 5.2, entry 7) (Scheme 5.1). A reaction carried out with 1000 equiv. of Et_3SiH and 5 equiv. of *n*-Bu_4NBr at a CO_2 pressure of 20 bar at 140 °C in THF run for 18 h showed the formation of $MeOSiEt_3$ with TON of 160 (Table 5.2, entry 8). This reaction with the addition of 2 equiv. of $B(C_6F_6)_3$ with respect to **IIIA** gave $MeOSiEt_3$ with a TON of 420 (Table 5.2, entry 8). Reaction between $B(C_6F_6)_3$ and silane is expected to generate the silylium ion $[Et_3Si]^+$ eventually adding to the NO ligand and inducing nitrosyl bending.[13a] Thus the quite substantial increase in activity is attributed to be

a consequence of the generation of vacant sites, as well as the enhancement of splitting of dihydrogen in a bifunctional manner across $[Re\text{-}NOSiR_3]^+$ bond.

5.2.3. Mechanistic Studies

To understand the mechanism of these reactions, we refer to Chapter 2. The bromide ligand *trans* to the nitrosyl ligand is comparatively strongly bonded to the rhenium centre due to a strong push pull interaction of the Br-Re-NO axis. This is revealed in the reactivity of **IIIA** with Et_3SiH, which led to formation of the rhenium silane dihydride species **IVA**, analyzed in solution (Scheme 5.2). This reacted with 2 bar ethylene gave rise to a η^2-ethylene coordinated complex forming stable 4-membered rhenacycles through the activation of a *ortho*-C-H of one of the phenyl groups attached to a phosphorus atom, presumably due to the incapability of the rhenium hydride bond to be stabilized *trans* to the large bite angle sixantphos ligand. These rhenacycles where found to react with hydrogen to form H-bridged dinuclear complexes of type **X,** from which the coordinatively unsaturated rhenium monohydride monomer **V** was thought to be released as the active species. Analogous complexes bearing comparatively smaller bite angle diphosphine ligands than Sixantphos furnished rhenium complexes bearing an ethylene ligand and a H disposed *cis* to each other. However, in either case, the bromide ligand *trans* to NO ligand was not affected. However, in the presence of *n*-Bu_4NBr, complex **XVIIIA** can be formed where the site *trans* to NO ligand is accessible (Scheme 5.2).

Combining these experimental evidences and facts, a Re(III) species **XXVIA** is assumed to be formed when **IIIA** is reacted with *n*-Bu_4Br and Et_3SiH (Scheme 5.2). This species would be in equilibrium with the coordinatively unsaturated 16e [Re]-H species **XXVIIA** analogous to the equilibrium between **IVA** and **VA** (Chapter 2). CO_2 insertion into the Re-H bond of **XXVIIA** would give rise to the coordinatively unsaturated formate species



Scheme 5.2. Proposed mechanism of hydrosilyation/hydrogenation of CO_2 to silylformate using complex **IIIA**.

XXVIIIA. This can react with either H_2 or Et_3SiH to form species **XXIXA** and **XXXA,** respectively. Upon reductive elimination of H(CO)OH would regenerate the active species **XXVIIA**. The formic acid elimination is favoured due to the formation of $H(CO)OSiEt_3$ releasing H_2. However, reductive elimination of $H(CO)OSiEt_3$ rather than H(CO)OH is apparently preferred from **XXXA,** since no hydrogen could be observed in the hydrosilylation route. The formed $H(CO)OSiEt_3$ could undergo further hydrogenation as well as hydrosilylation step as depicted in scheme 5.1.

5.3. Conclusion

In conclusion, homogeneous hydrogenation and hydrosilylation of CO_2 to methanol could be

realized using suitable large bite angle diphosphine nitrosyl rhenium complexes. A preliminary mechanism for the Et_3SiH and *n*-Bu_4NBr co-catalyzed hydrogenation/hydrosilylation is proposed with formation of a crucial coordinatively unsaturated rhenium dihydride as the active species. This catalysis, particularly the air stable variant of these hydrogenations would impart opportunity for the development of efficient robust catalytic systems for these important transformations.

5.4. Experimental Section

Unless mentioned, all manipulations of addition of reaction components and samplings were done in a glove box filled with dry N_2. All the reagents are purchased from either Aldrich or ABCR chemical company and used without further purification.

5.5.1. Preparation of $[Re_2(A)_2\mu^3\text{-}(OH)_3(NO)_2]^+Br^-$ (XXVA)

Complex **IIIA** (20 mg, 0.0198 mmol) and sodium formate (15.93 mg, 0.0988 mmol) was taken in a Young NMR tube and acetone (LR grade, 0.2 mL) was added to it. It was heated to 50 °C for 2 h. The mass was cooled to room temperature, concentrated to dryness. The residue was extracted with CH_2Cl_2 (2 x 0.5 mL), concentrated and dried to get the product **XXIA** as off-white to pale gray solid. The reaction leading to this product could not be reproduced even with dry or moist acetone and/or with NaOH since attempts gave rise to inseparable mixture of products. Yield: (12.47 mg. 0.0071 mmol, 72%; IR (KBr, cm^{-1}): 3466 (br, m), 3409 (br, m), 3047 (w), 2924 (w), 1686 (s), 1560 (w), 1434 (m), 1380 (s), 1247 (w), 1228 (w), 1121 (w), 1090 (w); ^1H NMR (500 MHz, $CDCl_3$): δ 0.38 (s, 3H), 0.63 (s, 3H), 0.65 (s, 3H), 1.33 (s, 3H), 5.59 (t, 4H, *J* = 7.5 Hz), 6.13 (t, 2H, *J* = 9 Hz) , 6.47 (t, 4H, *J* = 10.2 Hz), 6.58-6.62 (m, 4H), 6.67 (m, 6H), 6.90 (t, J = 8.3 Hz, 2H), 7.05 (t, J = 7.0 Hz, 2H), 7.09 (t, J = 7.5 Hz, 2H), 7.22 (t, J = 7.3 Hz, 4H), 7.32 (t, *J* = 7.3 Hz, 2H), 7.48-7.56 (m, 6H), 7.65 (d, J = 7.5 Hz, 4H), 8.19 (d, J = 7.0 Hz) 4H); $^{31}P\{^1H\}$ NMR (121 MHz, $CDCl_3$): δ 3.0 (s), 14.4 (s); Anal. (%). Calc for $C_{76}H_{67}BrN_2O_7P_4Re_2Si_2$: C, 52.08; H, 3.85; N, 1.60. Found: C, 50.81; H, 4.15; N, 1.37 (not satisfactory due to the presence of inseparable impurities).

5.5.2. Hydrogenation of Carbon Dioxide

Complex **IIIA** (5 mg, 0.00494 mmol) and Bu_4NBr (7.96 mg, 0.0247 mmol) was taken in a stainless steel autoclave. THF (1 mL) was added to it. The vessel was pressurized with 20 bar of CO_2 (the pressure decreased to 18 bar) and then with 60 bar of H_2 (Total to 78 bar). It was heated to 140 °C for 18 h. The vessel was cooled

to 0° C using an ice bath. The gases were slowly wented in to a fume hood. Immediately after opening the vessel, 10 µL of DMF was added to it as an internal standard and shaken well. Little of this solution (approx. µL) was taken using a pipette and placed the pipette in an NMR tube followed by immediate dilution of this solution with appropriate quantity of D_2O injected through the same pipette. The content of methanol is quantified by ^{1}H NMR spectroscopy by integrating its methyl protons against the methyl protons of DMF.

^{1}H NMR (D_2O, 300 MHz, 10 µL DMF): δ 3.22 (s; MeOH), 2.89 and 2.74 (both s, DMF).

5.5.3. Hydrogenation/Hydrosilylation of Carbon Dioxide

The above procedure was followed, but with the addition of appropriate quantity of Et_3SiH, as a reaction component. To quantify MeOH and Et_3SiOMe separately, samples were taken in a glove box and analyzed by ^{1}H NMR in dry THF-d_8 using dry DMF as internal standard.

^{1}H NMR (THF-d_8, 300 MHz, 10 µL DMF): δ 3.44 (s; MeOSiEt$_3$), 3.29 (s; MeOH); 2.89 and 2.78 (both s, DMF).

5.5.4. Hydrosilylation of Carbon Dioxide

A similar procedure as in 5.5.3 was adopted, but no H_2 was charged. The sampling was done in glove box, analyzed by ^{1}H NMR spectroscopy in dry THF using dry mesitylene as internal standard.

^{1}H NMR (THF-d_8, 300 MHz, mesitylene): 3.44 (s, MeOSiEt$_3$), 8.08 (H(CO)SiEt$_3$), 2.24 (s, mesitylene); 2.91 and 2.78 (s, both DMF).

5.5. References

1. *IPCC Fourth Assessment Report: Climate Change 2007: Synthesis Report; Chapter 2.2.*
2. *Annual Energy Review 2011; U.**S**. Energy Information Administration: Washington, DC, 2012;Table 11.1,* pp 302-303.
3. *USGS World Petroleum Assessment 2000 and US DOE IEA 1999, World Energy Overview.*
4. N. S. Lewis, D. G. Nocera, *Proc. Natl. Acad. Sci.* U.S.A. **2006**, *103*, 15729.
5. a) K. Ushikoshi, K. Mori, T. Watanabe, M. Takeuchi, M. Saito, *Stud. Surf. Sci. Catal*. **1998**, 114, 357; b) M. Saito, *Catal. Surv. Jpn*. **1998**, 175; c) L. C. Grabow, M. Mavrikakis, *ACS Catal*. **2011**, *1*,365.
6. P. W. N. M. van Leeuwen, in *Homogeneous Catalysis; Understanding the art* ; Kluwer Academic Publisher; Dordrecht, The Netherlands.
7. R. J. Wijngaarden, K. R. Westerterp, A. Kronberg, in *Industrial catalysis: optimizing catalysts and processes*; Wiley-VCH: Weinheim, **2009.**
8. a) I. Karamé, In *Hydrogenation*; Ch. 10: InTech: Rijeka, Croatia, **2012**; b) P. G. Jessop, F. Joó, C.-C. Tai, *Coord. Chem. Rev*. **2004,** *248,* 2425-2442**;** c). W. Wang, S. Wang, X. Ma, J. Gong, *Chem. Soc. Rev*. **2011**, *40,* 3703-3727.
9. E. Balaraman, C. Gunanathan, J. Zhang, L. J. W. Shimon, D. Milstein. *Nat. Chem*. **2011**, *3*, 609-614.

10. a) S. Chakraborty, J. Zhang, J. A. Krause, H. Guan, *J. Am. Chem. Soc*. **2010**, *132*, 8872; b) S. N. Riduan, Y. Zhang, J. Y. Ying, *Angew. Chem.* **2009**, *121*, 3372-3375; c) M.-A. Courtemanche, M.-A. Légaré, L. Maron, F.-G. Fontaine, *J. Am. Chem. Soc*. **2013**, *135*, 9326-9329
11. C. A. Huff, M. S. Sanford, *J. Am. Chem. Soc.* **2011**, *133*, 18122-18125.
12. S. Wesselbaum, T. vom Stein, J. Klankermayer, W. Leitner, *Angew. Chem., Int. Ed.* **2012**, *51*, 7499-7502.
13. a) Y. Jiang, B. Schirmer, O. Blacque, T. Fox, S. Grimme, H. Berke, *J. Am. Chem. Soc*. **2013**, *135*, 4088-4102; b) Y. Jiang, J. Hess, T. Fox, H. Berke, H. *J. Am. Chem. Soc*. **2010**, *132*, 18233-18247.
14. Y. Jiang, O. Blacque, T. Fox, H. Berke, *J. Am. Chem. Soc*. **2013**, *135*, 7751-7760.
15. a) R. R. Schrock, J. A. Osborn, *J. Am. Chem. Soc.* **1976**, *98*, 2134; b) R. R. Schrock, J. A. Osborn, *J. Am. Chem. Soc*. **1976**, *98*, 4450; c) R. H. Crabtree, A. Gautier, G. Giordano, and T. Khan, *J. Organometal. Chem.* **1977**, *141*, 113; d) H. Berke, P. Burger, *Comments Inorg.Chem*. **1994**, *16*, 279-312; e) H. Jacobsen, H. Berke, in *Recent Advances in Hydride Chemistry*; (Ed.: R. Poli), Elsevier: Amsterdam, Holland, **2001**; pp 89-116; f) A. Choualeb, E. Maccaroni, O. Blacque, H. W. Schmalle, H. Berke, *Organometallics* **2008**, *27*, 3474-3481.

Homogeneous Hydrogenations of Aldehydes, Ketones, Esters and Bicarbonates to Alcohols, as well as Carbon Dioxide and Bicarbonates to Formates Catalyzed by Rhenium Complexes

6.1. Introduction

The reduction of carbonyl compounds: aldehydes, ketones, carboxylic acids and its derivatives like esters and anhydrides to their corresponding alcohols is one of the fundamental reactions in synthetic organic chemistry.[1] Alcohols are important building blocks of intermediates and fine chemicals, pharmaceuticals and agrochemicals.[2] Though $NaBH_4$, $LiAlH_4$ and other stoichiometric hydride reagents including silanes are frequently used for these transformations on a laboratoty scale, the disadvantages of very low atom economy, high cost, environmentally unfriendly or not "green" and tedious work up procedures leading to large amount of waste, limit their use in industrial processes.[3] Heterogeneous catalytic systems such as Pd/C and Pt/C are often used for the hydrogenation of these carbonyl compounds, but the requirement of harsh reaction conditions, intolerance to functional groups are the major disadvantages of these systems.[2] To overcome these, there is a substantial interest in developing suitable homogeneous catalytic processes.

A number of homogeneous catalytic systems are reported for the hydrogenation of aldehydes and ketones and are often based on the platinum group metals Ir, Rh and Ru and Pd.[4] The complex $[RuCl_2(CO)_2(PPh_3)_2]$ could hydrogenate a series of aldehydes at 15 bar H_2 with TONs of up to 56000 for benzaldehyde at 180 °C and 59400 for 2-methylpentanal at 160 °C with TOFs of 4000 h^{-1} and 4950 h^{-1}, respectively. These are amongst the highest

TONs reported for aldehyde hydrogenations.[5] Recently, Milstein and co-workers developed efficient Fe based catalytic systems capable of hydrogenating a variety of and ketones.[6] Quite recently, Beller and co-workers have also demonstrated an effective Fe based catalytic system capable of hydrogenating aldehydes and ketones.[2]

The hydrogenation of esters, bicarbonates and carbon dioxide is a difficult task. However, sufficient attention has been paid to these transformations in the recent past.[7,8,9] Though efficient methods for ester hydrogenations to the corresponding alcohols[7] were achieved, the reported hydrogenations of bicarbonates or carbonates could be taken to only to the level of formates and not alcohols.[8] The hydrogenation of carbon dioxide to formate level has been extensively studied, but it is dominated by Ru systems.[8e,f,9]

The thermodynamics of the hydrogenation of CO_2 to formic acid is limited by a negative value of entropy (eq. 1).[9a] Addition of a base to this reaction can improve the enthalpy, while dissolution of the gases would improve the entropy (eqs. 2-3).

$$CO_2(g) + H_2(g) \rightarrow H(CO)OH(l) \qquad \text{(eq. 1)}$$

$$\Delta G^o = 32.9 \text{ kJ/mol}; \Delta H^o = -31.2 \text{ kJ/mol}; \Delta S^o = -215 \text{ J/(mol K)}$$

$$CO_2(g) + H_2(g) + NH_3\,(aq) \rightarrow H(CO)O^-\,(aq) + NH_4^+(aq) \qquad \text{(eq. 2)}$$

$$\Delta G^o = -9.5 \text{ kJ/mol}; \Delta H^o = -84.3 \text{ kJ/mol}; \Delta S^o = -250 \text{ J/(mol K)}$$

$$CO_2(aq) + H_2(aq) + NH_3\,(aq) \rightarrow H(CO)O^-\,(aq) + NH_4^+(aq) \qquad \text{(eq. 3)}$$

$$\Delta G^o = -35.4 \text{ kJ/mol}; \Delta H^o = -59.8 \text{ kJ/mol}; \Delta S^o = -81 \text{ J/(mol K)}$$

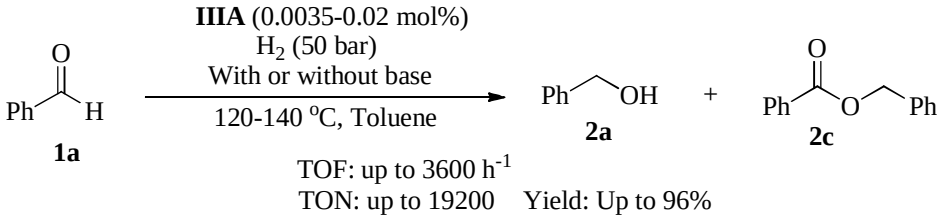
6.2. Results and Discussion

6.2.1. Hydrogenation of Aldehydes Catalyzed by IIIA

We have tested complex **IIIA** for the hydrogenation of benzaldehyde under a pressure of 50 bar H_2 at 140 °C in toluene. With 0.02 mol% of **IIIA**, a TOF of 200 h^{-1} was observed in completing the reaction in 24 h with 96% yield of benzyl alcohol in 99% conversion (Table

6.1, entry 1). Via a Claisen-Tishchenko reaction 3% of benzyl benzoate was also obtained. However, addition of 0.35 mol% of Et_3SiH drastically increased the rate of the reaction. Applying 0.0035 mol% loading of **IIIA**, 61% of benzyl alcohol was obtained in 17 h in 71% conversion; remaining being 4% of a hydrosilylated product, benzyl triethylsilyl ether, apart from 6% of benzyl benzoate (Table 6.1, entry 2). When the reaction was carried out with 0.02 mol% loading of **IIIA** and 0.25 mol% of *t*-BuOK as co-catalyst, the reaction showed complete conversion in 2 h with 90% yield of benzyl alcohol along with 9% yield of the ester (Table 6.1, entry 3). At this point, it is worth mentioning that *t*-BuOK alone is an active catalyst for the Claisen-Tischenko disproportionation of benzaldehyde to benzyl benzoate which we reported recently.[10] Thus, in order to suppress the formation of benzyl benzoate,

Table 6.1. Hydrogenation of benzaldehyde catalyzed by **IIIA**[a]



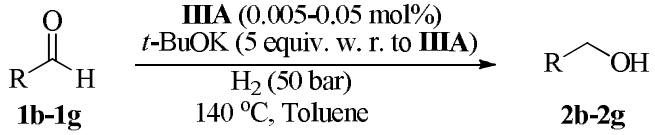
Entry	**IIIA** (mol%)	Additive (mol%)	Time (h)	TOF (h^{-1})	TON	Yield (**2a**, %)	Ester (**2c**, %)	Conv. (%)
1	0.02	-	24	200	4807	96	3	99
2	0.0035	Et_3SiH/0.35	17	1035	17600	61	6	71[b]
3	0.02	*t*-BuOK/0.25	2	2250	4500	90	9	99
4	0.01	*t*-BuOK /0.12	4	2400	9600	96	3	99
5	0.005	*t*-BuOK /0.06	1	3600	3600	18	2	20
			9	2133	19200	96	3	99
6	0.005	KOH/0.06	1	2967	2967	15	1	16
7	0.005	*t*-BuOK /0.06 +TBAB/8	1	2855	2855	14	1	15
8	0.01	*t*-BuOK /0.06	16	294	4700	47	3	50[c]

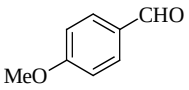
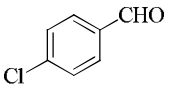
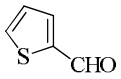
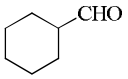
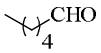
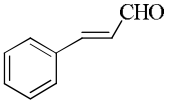
[a]Yield by GC/MS based on the consumption of benzaldehyde; [b]4% of hydrosilylated product. [c]Reaction was carried out at 120 °C.

we further reduced the amount of *t*-BuOK to 0.06 mol% and a run of the reaction with a loading of 0.005 mol% of **IIIA** furnished benzyl alcohol with a TOF of 2133 h^{-1} (3600 h^{-1} in the first h) and a TON of 19200 in 96% yield along with 3% of the ester within a reaction time of 9 h (Table 6.1, entry 5). A batch using KOH as a base, as well as one with the addition of 5 equiv. of *n*-Bu_4NBr in addition to *t*-BuOK as a base was found to be somewhat less active when compared to the action using only *t*-BuOK as base. A run of the reaction with a 0.01 mol% loading carried out at a pressure of 20 bar at 120 °C showed a TOF of 294 h^{-1} with 50% conversion in 16 h giving rise to 47% yield of benzyl alcohol.

The generality of this reaction using **IIIA** with addition of *t*-BuOK (5 equiv. with respect to **IIIA**) was then applied to a variety of aliphatic, aromatic and heteroaromatic aldehydes and ketones (Table 6.2). With a loading of 0.005 mol% of **IIIA**, 4-anisaldehyde was hydrogenated quantitatively to 4-methozybenzylalcohol in 7 h with a TOF of 2857 h^{-1} (Table 6.2, entry 1). Surprisingly, no competing Claisen-Tishchenko reaction was observed. Similarly, applying a loading of 0.02 mol% of **IIIA**, 4-chlorobenzaldehyde was hydrogenated quantitatively to 4-chlorobenzyl alcohol in 4 h with a TOF of 1250 h^{-1} (Table 6.2, entry 2). The heteroaromatic aldehydes 2-thiophenecarboxaldehyde could be hydrogenated to the corresponding alcohol when a catalyst loading of 0.02 mol% was adopted giving rise to 95% yield of the corresponding alcohol with 4% of the Claisen-Tishchenko ester in 4 h (Table 6.2, entry 3). With a catalyst loading of 0.02 mol%, the aliphatic aldehydes, cyclohexanecarboxaldehyde showed a TOF of 3920 h^{-1} forming 98% of the corresponding alcohol along with < 2% of the ester completing it in 1.25 h (Table 6.2, entry 4). However, under these conditions, 1-hexanal showed a TOF of 4511 h^{-1} furnishing 90% yield of 1-hexanol remaining being the ester with almost complete conversion (Table 6.2, entry 5). The formation of the ester in comparatively high amount is anticipated to be due to the ability of

Table 6.2. Hydrogenation of various aldehydes catalyzed by **IIIA**[a]



Entry	Aldehyde (**1**)		**IIIA** (mol%)	Time (h)	TOF (h^{-1})	TON	Alcohol, Yield (**2**, %)	Conv. (%)
1		**1b**	0.005	7	2857	20000	> 99	> 99
2		**1c**	0.02	4	1250	5000	> 99	> 99
3		**1d**	0.02	4	1125	4500	95	> 99
4		**1e**	0.02	1.25	3920	4900	98	99
5		**1f**	0.02	1	-	4500	90	> 99
6		**1g**	0.05	24	-	219	11	-[b]
7		**1h**	0.05	2	960	1920	96	> 99

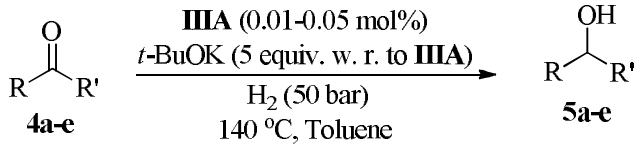
[a]Yield by GC/MS based on the consumption of substrate. [b]Paraformaldehyde was used as the substrate and yield by ^{1}H NMR spectroscopy using DMF as an internal standard.

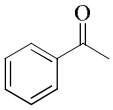
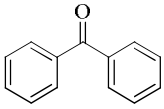
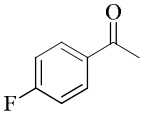
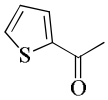
t-BuOK to catalyze the Claisen-Tishchenko reaction of hexanal at room temperature.[10] With a loading of 0.05 mol% of **IIIA**, paraformaldehyde furnished methanol with a TON of 219 and a yield of 11% in 24 h (Table 6.2, entry 6). α,β-unsaturated aldehyde, *trans*-cinnamaldehyde was seen to give 96% yield of 3-phenylpropanol formed by hydrogenation of both the double bonds with a TOF of 960 h^{-1}, when a loading of 0.05 mol% of **IIIA** was adopted (Table 6.2, entry 7).

6.2.2. Hydrogenation of Ketones Catalyzed by IIIA

Ketones were found to be much more difficult to be hydrogenated when compared to aldehydes. With a loading of 0.05 mol% of catalyst **IIIA**, acetophenone could be hydrogenated quantitatively to the corresponding alcohol, *rac*-1-phenylethanol in 12 h (Table 6.3, entry 1). However, under these conditions, benzophenone gave only 30% yield of the product, diphenylmethanol (**5b)** (Table 6.3, entry 2). 4'-Fluoroacetophenone could be hydrogenated to the corresponding alcohol *rac*-1-(4-fluorophenyl)ethanol **(5c)** in 97% yield when a catalyst loading of 0.05 mol% was adopted (Table 6.3, entry 3). However, under these conditions, the heteroaromatic ketone, 2-acetylthiophene was found to give a yield of only 14% of the corresponding alcohol *rac*-1-(2-thienyl)ethanol **(5d)** in 12 h (Table 6.3, entry 4).

Table 6.3. Hydrogenation of various ketones catalyzed by **IIIA**[a]



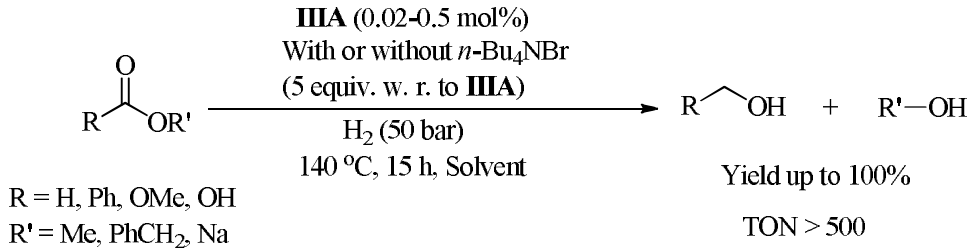
Entry	Ketone (**4**)		**IIIA** (mol%)	TOF (h^{-1})	TON	Yield (**5**, %)
1		**4a**	0.05	167	2000	> 99
2		**4b**	0.05	50	600	30
3		**4c**	0.05	162	1940	97
4		**4d**	0.05	23	280	14
5		**4e**	0.05	-	< 100	< 5

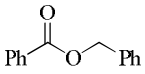
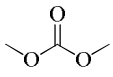
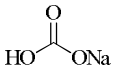
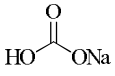
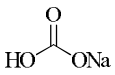
[a]All the reactions were run for 12 h, yield by GC/MS based on the consumption of substrate, conversion and yield are same for entries 1-4 and for entry 5, 15% of aldol products were observed.

Under these conditions, attempts to hydrogenate aliphatic ketones, like for instance cyclohexanone led to the formation of < 5% of cyclohexanol in 12 h, instead aldol products were found to dominate which presumably points to a catalysis of *t*-BuOK (Table 6.3, entry 5).

6.2.3. Hydrogenation of Esters and Bicarbonates to Alcohols Catalyzed by IIIA

Table 6.4. Hydrogenation of esters to alcohols and sodium bicarbonate to sodium formate or alcohols catalyzed by **IIIA**[a]



Entry	Substrate	**IIIA** (mol%)	Co-catalyst	Solvent	Product	TON	Yield (%)
1		0.02	*n*-Bu_4NBr	THF	$PhCH_2OH$	500	100
2		0.5	-	THF	CH_3OH	112	56
3		0.5	*n*-Bu_4NBr	EtOH	CH_3OH	161	81
4		0.2	-	MeOH	H(CO)ONa	28	5.6
5		0.2	-	D_2O/THF	H(CO)ONa	68	13.6
6		0.5	*n*-Bu_4NBr	EtOH	CH_3OH H(CO)ONa	20 24	10 12

[a]All reactions were carried out under 50 bar of H_2 at 140 °C run for 15 h. For entry 1, yield by GC/Ms based on the consumption of benzyl benzoate and for entries 2-6, yield by ^1H NMR spectroscopy using DMF, THF or dioxane as an internal standard.

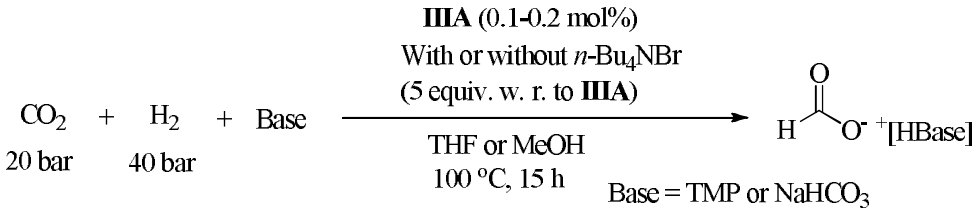
Then, we tested the activity of complex **IIIA** in the hydrogenation of esters at pressure of 50 bar and at a temperature of 140 °C in THF. With a loading of 0.2 mol% of **IIIA** along with 1 mol% of *n*-Bu_4NBr, the hydrogenation of benzyl benzoate was effected showing a TOF of > 500 h^{-1} giving rise to a quantitative yield of benzyl alcohol in < 1 h (Table 6.4, entry 5). However, without the addition of base, a TON of 112 was achieved in 18 h for the hydrogenation of methyl formate to methanol when a catalyst loading of 0.5 mol% was adopted, as quantified by ^1H NMR using DMF as internal standard (Table 6.4, entry 2). The carbonic acid ester, dimethylcarbonate furnished methanol in TON of 161 when run for 18 h upon hydrogenation with a loading of 0.5 mol% of **IIIA** along with 5 equiv. of *n*-Bu_4NBr (Table 6.4, entry 3).

Then, we applied **IIIA** as a catalyst in the hydrogenation of sodium bicarbonate under the above conditions. Thus, with a loading of 0.5 mol% of **IIIA** along with 5 equiv. of *n*-Bu_4NBr, methanol was produced with a TON of 20 and sodium formate with a TON of 24 (Table 6.4, entry 6). It is worth mentioning at this stage that the hydrogenation of carbonates or bicarbonates to methanol is unique finding and has not yet been reported in the literature.

6.2.4. Hydrogenation of Carbon Dioxide and Bicarbonates to Formates Catalyzed by IIIA

We then applied catalyst **IIIA** for the hydrogenation of carbon dioxide with pCO_2 : pH_2 = 20 : 40 at a temperature of 100 °C in the presence of 2,2,6,6-tetramethylpiperidine (TMP) or sodium bicarbonate (Table 6.5). TMP or the bicarbonate is anticipated to function as a base and in the absence of any other additive, reaction showed a TON of 7 when a loading of 0.2 mol% was adopted in THF. With a loading of 0.2 mol% of **IIIA** and TMP as a base along with 5 equiv. of *t*-BuOK in THF gave rise to formate with a TON of 38 whereas reaction without *t*-BuOK gave a TON of 31 (Table 6.5, entries 2 and 3). It is worth mentioning that methanol could not be observed in these reactions. Using $NaHCO_3$, with a

Table 6.5. Hydrogenation of CO_2 to formates catalyzed by **IIIA** [a]



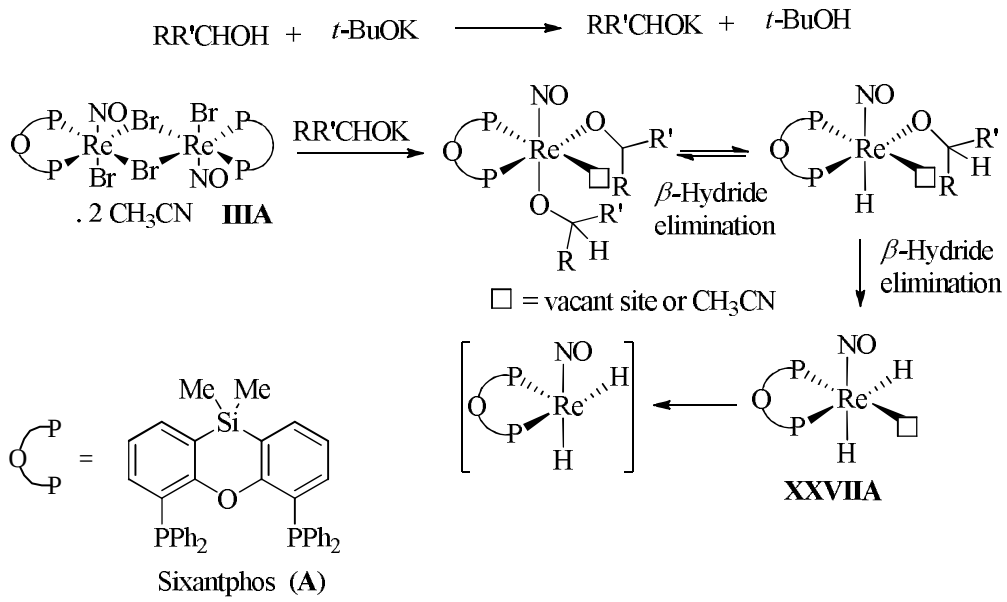
Entry	**IIIA** (mol%)	Base	Solvent	TON	Yield (%)
1	0.2	TMP	THF	7	3.5
2	0.2	TMP	THF-d_8	38	19 [b]
3	0.2	TMP	THF	31	15.5
4	0.1	$NaHCO_3$	MeOH	605	60.5

[a]Catalyst loading and yield with respect to base; yield by ^{1}H NMR spectroscopy using DMF as internal standard. [b]5 equiv. of *t*-BuOK w. r. to IIIA was added.

loading of 0.1 mol% of **IIIA** along with 5 equiv. of *n*-Bu_4NBr, a TON of 605 could be achieved when the reaction was carried out in methanol (Table 6.5, entry 4).

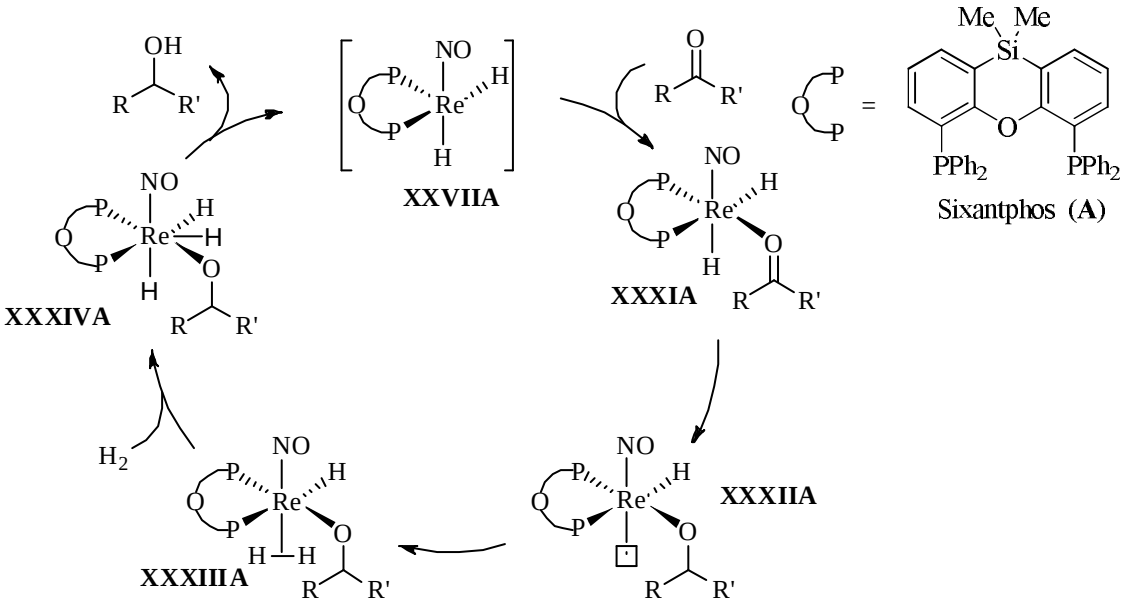
6.2.5. Mechanistic Aspects

Conclusive separate experiments to understand the mechanism of the hydrogenation of either aldehydes, ketones, esters or bicarbonates could not be carried out. However, a mechanism was expected to operate analogous to the one described for the imine hydrogenations using **IIIA** which is also operative for hydrogenations of aldehydes or ketones without the presence of a base (Chapter 4). The accelerating influence of the addition of bromide should however be the same as described in Scheme 4.2 of Chapter 4. It is worth noting that the reaction without a base was much slower in rate when compared to those with the addition of a base. Sampling of the hydrogenation reaction of acetopheneone and 4′-fluoroacetopheneone

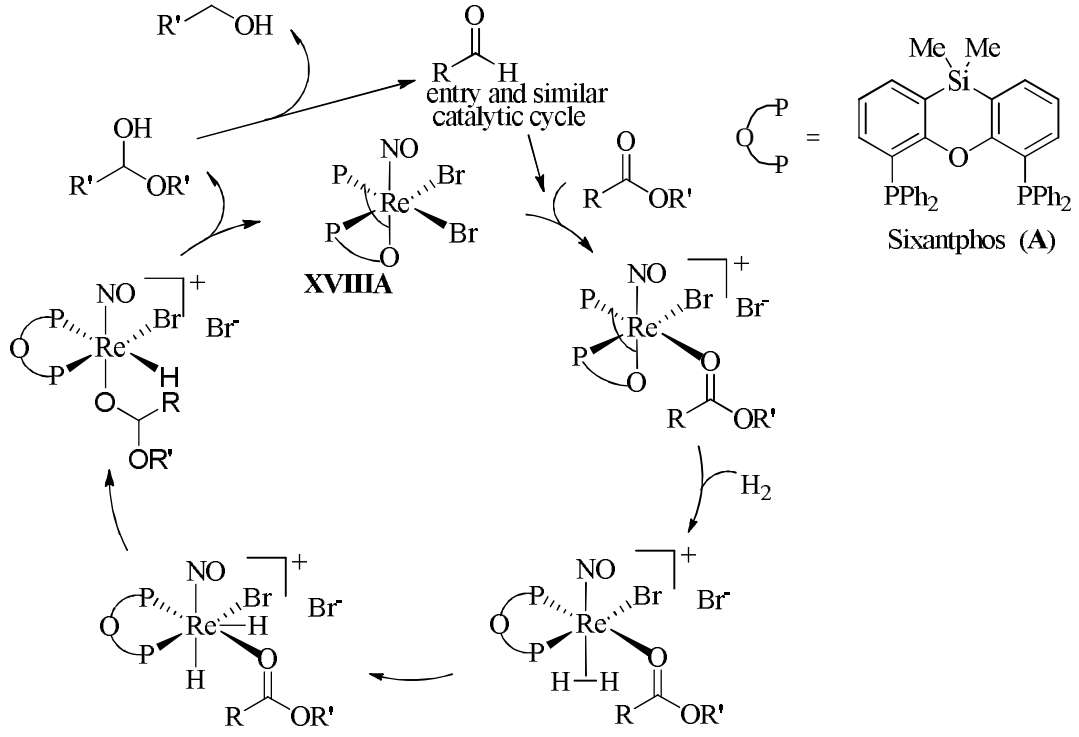


Scheme 6.1. Formation of active species **XXVIIA** by the reaction of **IIIA** with *t*-BuOK and alcohol.

catalyzed by **IIIA** in the presence of *t*-BuOK showed only 6% and 2% conversions, respectively, in the first one hour whereas both these reactions were completed in 12 h suggests that the mechanism involving a bromide dissociation as described for the hydrogenation of imines (Chapter 4) is presumably operative at least for initial few cycles to form alcohols. However the complex **IIIA** showed no reaction with *t*-BuOK, but reacted in the presence of 2-propanol to induce catalytic transfer hydrogenations of ketones and imines (Chapter 7). A mechanism involving a rhenium dihydride (**XXVIIA**, generated by the reaction of potassium isopropoxide with **IIIA**) as the active species is suggested for this transfer hydrogenation reactions. Thus, in the case of hydrogenation reactions of aldehydes and ketones, the corresponding potassium alkoxides formed in the course of the hydrogenation reaction is expected to generate rhenium dihydide species **XXVII**A as proposed for the hydrogenation/hydrosilylation of carbon dioxide in Chapter 5, as well as the transfer hydrogenation reactions of ketones and imines in Chapter 7 (Scheme 6.1). Thus, in the hydrogenation of aldehydes and ketones, the observed increase in the reaction rates after a



Scheme 6.2. Proposed catalytic cycle for the hydrogenation of aldehydes and ketones catalyzed by **IIIA**/*t*-BuOK system.



Scheme 6.3. Proposed mechanism for the hydrogenation of esters catalyzed by **IIIA**.

certain period of time is thought to be a result of the formation of the corresponding potassium alkoxide in the reaction medium.

Coordination of the substrate to the active species **XXVIIA** followed by insertion of it into the rhenium hydrides bond *trans* to NO ligand would generate a coordinatively unsaturated 16e species **XXXIIA** (Scheme 6.2). Coordination of H_2 followed by oxidative addition to **XXXIIA** would generate the rhenium(III) complex **XXXIVA**. This would reductively eliminate the alcohol and regenerate the active species **XXVIIA**.

The mechanism for the hydrogenation of esters is assumed to be analogoues to the one discussed for the hydrogenation of imines (Scheme 6.3). The ester would naturally form first an aldehyde and an alcohol. The aldehyde would enter in to the catalytic cycle there by hydrogenating it to alcohol.

6.3. Conclusion

Highly efficient homogeneous hydrogenations of aldehydes and ketones were realized using nitrosyl diphosphine rhenium complexes in the presence or absence of a base. The presented rhenium system represents one of the most active systems hydrogenation of aldehydes compared to those reported in the literature. Claisen-Tishchenko disproportionations of aldehydes to esters catalyzed by rhenium hydride species as well as *t*-BuOK were seen to be side reactions in some cases. This could be minimized by reducing the amount of *t*-BuOK. These esters formed as side products can be assumed to be hydrogenated under the given catalytic conditions. Efficient hydrogenations of esters including that of methyl formate to methanol could be also achieved. Both carbon dioxide and sodium bicarbonate could be hydrogenated to the formate level and when controlling the reaction conditions these furnished methanol as the hydrogenation product. The reaction yielding methanol by the hydrogenation of carbon dioxide was already discussed in Chapter 5. Finally, a plausible

mechanism for the hydrogenations of aldehydes and ketones, as well as of esters could be established.

6.4. Experimental Section

All manipulations of addition of reaction components and samplings were done in a glove box filled with dry N_2. All the reagents are purchased from either Aldrich or ABCR chemical company and used without further purification.

Typical Procedure for the Hydrogenation of Aldehydes and Ketones

Catalyst **IIIA** (0.005 g, 0.00494 mmol), benzaldehyde (10.476 g, 98.81 mmol), *t*-BuOK (0.0067 g, 0.059 mmol) was taken in a 50 mL stainless steel autoclave and toluene (10 mL) was added to it. The vessel was closed and connected to a Büchi pressflow gas controller machine. The gas line was evacuated thrice and the line was charged with approx. 3 bar of H_2. The vessel was opened and it was evacuated carefully (thrice, not allowing pressure to go below 0 bar) to remove nitrogen. It was then charged with H_2 (50 bar) and kept in an oil bath maintained at 140 °C. The consumption of the gas is measured from the graph, from which the conversion of benzaldehyde could be calculated (For reactions with a low volume of substrate, the vessel was charged with 50 bar H_2 and kept in an oil bath maintained at 140 °C). After appropriate time, the vessel was cooled to room temperature, H_2 was slowly released in a fume hood. The sample was taken, diluted with dichloromethane and analyzed by GC/MS (CP-3800 Saturn 2000MS/MS spectrometer, Column: Brechbuhler, ZB-5ms, 30m x 0.25mm x 0.25μm). The yield of the benzyl alcohol was calculated based on the consumption of benzaldehyde.

Benzaldehyde (**1a**): 3.65 min (m/z = 106); Benzyl alcohol (**2a**): 4.19 min (m/z = 108); Benzyl benzoate (**3a**): 9.61 min (m/z = 112).

GC/MS Data for other compounds (compound: retention time (mass peak)): **1b**: 6.06 min (m/z = 136); **2b**: 6.22 min (m/z = 138); **1c**: 5.00 min (m/z: 140); **2c:** 5.86 min (m/z = 142); **1d**: 3.93 min (m/z = 112); **2d**: 4.12 min (m/z = 114); **3d**: 8.32 min (224); **1e**: 3.45 min (m/z = 112); **2e**: 3.93 min (m/z = 114); **3e**: 9.20 min (m/z = 224); **1f**: 1.81 min (m/z: 100); **2f**: 2.82 min (m/z = 102); **1g**: 4.19 min (m/z = 132); **2g**: 6.42 min (m/z = 136); **3f**: 6.83 min (m/z = 200); **4a**: 4.44 min (m/z = 120); **5a**: 4.37 min (m/z: 122); **4b**: 35.51 min (m/z = 182); **5b**: 36.00 min (m/z = 184); **4c**: 4.34 min (m/z = 138); **5c**: 4.47 min (m/z = 140); **4d**: 4.37 min (m/z = 126); **5d**: 4.67 min (m/z = 128); **4e**: 3.10 min (m/z = 98); **5e**: 3.02 min (m/z = 100).

Typical Procedure for the Hydrogenation of Esters and Sodium Bicarbonate

Catalyst **IIIA** (0.005 g, 0.00494 mmol), benzyl benzoate (0.524 g, 2.47 mmol), *n*-Bu_4NBr (0.008 g, 0.0247 mmol) was taken in a stainless steel autoclave and THF (1 mL) was added to it. The vessel was then charged with H_2 (50 bar) and kept in an oil bath maintained at 140 °C. After appropriate time, the vessel was cooled to room temperature, H_2 was slowly released in a fume hood. The sample was analyzed by GC/MS and yield was calculated based on the consumption of benzyl benzoate.

For reactions in Table 6.4, entries 2, 3 and 6, after the reaction, 10 µL of DMF was added as internal standard and the yield of methanol was calculated by ^{1}H NMR spectroscopy based the methyl peaks of DMF. For entry 6, the yield of sodium formate was determined based on the formyl H proton of DMF.

^{1}H NMR (D_2O, 300 MHz, 10 µL DMF): δ 3.22 (s; methanol), 2.89 and 2.74 (both s, DMF).

For reaction in Table 6.4, entry 4, the reactions mass was evaporated to dryness. The mixture is then weighed. From this, 20 mg was taken in an NMR tube. D_2O was added along with 10 µL of THF. The formate content was analyzed by ^{1}H NMR spectroscopy.

^{1}H NMR (D_2O, 300 MHz, 10 µL THF): δ 8.41 (s; sodium formate), 3.73 and 1.87 (both unresolved s, THF).

For reaction in Table 6.4, entry 4, the reactions mass was evaporated to dryness. D_2O was added to the whole mass along with 20 µL of dioxane. The formate content was analyzed by ^{1}H NMR spectroscopy.

^{1}H NMR (D_2O, 300 MHz, 20 µL dioxane for entry 4): δ 8.46 (s; sodium formate), 3.74 (s, dioxane).

Typical Procedure for the Hydrogenation of Carbon Dioxie to Formate Salts

Catalyst **IIIA** (0.005 g, 0.00494 mmol) and *n*-Bu_4NBr (0.008 g, 0.0247 mmol) was taken in a stainless steel autoclave and THF (1 mL) was added to it. The vessel was then charged with CO_2 (20 bar; note that a pressure reduction was observed and reached ~ 18 bar) followed by H_2 (40 bar; making a total pressure of ~ 58 bar) and it was kept in an oil bath maintained at 140 °C for 15 h with stirring. The vessel was cooled to room temperature, H_2 was slowly released in a fume hood. DMF (10 µL for entries 1-3 and 20 µL for entry 4) was added to the whole mass. The sample was analyzed by ^{1}H NMR spectroscopy. The formate content was determined based on the formyl H peak of DMF.

^{1}H NMR (D_2O, 300 MHz, 10 or 20 µL DMF): δ 8.31 (s; sodium formate), 7.81 (s, DMF).

6.5. References

1. H.-U. Blaser, C. Malan, B. Pugin, F. Spindler, H. Steiner, M. Studer, *Adv. Synth. Catal*. **2003**, *345*, 103-151.
2. S. Fleischer, S. Zhou, K. Junge, M. Beller. *Angew. Chem. Int. Ed*. **2013**, *52*, 5120-5124.

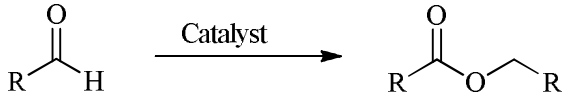
3. M. L. Clarke, G. J. Roff, in *Handbook of Homogeneous Hydrogenation*, (Eds.: J. G. de Vries, C. J. Elsevier), Wiley-VCH: Weinheim, **2007**; pp 413-437.
4. For reviews on this topic, see: a) F. Spindler, H.-U. Blaser in *Transition Metals for Organic Synthesis*, Vol. 2 (Eds.: M. Beller, C. Bolm), Wiley-VCH, Weinheim**, 2004**, p. 113; b) H.-U. Blaser, F. Spindler in *Handbook of Homogeneous Hydrogenation*, Vol. 3 (Eds.: J. G. de Vires, C. J. Elsevier), Wiley-VCH, Weinheim, **2007**, p. 1193; c) M. J. Palmer, M.Wills, *Tetrahedron: Asymmetry* **1999**, *10*, 2045-2061; d)W. Tang, X. Zhang, *Chem. Rev*. **2003**, *103*, 3029-3069; e) S.-L. You, *Chem. Asian J*. **2007**, *2*, 820-827; f) R. H. Morris, *Chem. Soc. Rev***. 2009**, 38, 2282-2291; g) T. C. Nugent, M. EI-Shazly, *Adv. Synth. Catal*. **2010**, *352*, 753-819; h) M. Rüping, E. Sugiono, F. R. Schoepke, *Synlett* **2010**, 852-865; i) N. Fleury-Brégeot, V. de La Fuente, S. Castillon, C. Claver, *ChemCatChem* **2010**, *2*, 1346- 1371; j) J.-H. Xie, S.-F. Zhu, Q.-L. Zhou, *Chem. Rev*. **2011**, *111*, 1713 -1760.
5. W. Strohmeier, L. Weigelt, *J. Organomet. Chem*. **1978**, *145*, 189.
6. a) R. Langer, G. Leitus, Y. Ben-David, D. Milstein, *Angew. Chem*. **2011**, *123*, 2168-2172; *Angew. Chem. Int. Ed*. **2011**, *50*, 2120-2124; b) R. Langer, M. A. Iron, L. Konstantinowsky, Y. DiskinPosner, G. Leitus, Y. Ben-David, D. Milstein, *Chem. Eur. J*. **2012**, *18*, 7196 -7209.
7. a) M. L. Clarke, *Catal. Sci. Technol*. **2012**, *2*, 2418-2423; W. N. O. Wylie, R. H. Morris, *ACS Catal.* **2013**, *3*, 32-40; b) E. Balaraman1, C. Gunanathan1, J. Zhang, L. J. W. Shimon, D. Milstein1, *Nat. Chem*. 2011, *3*, 609-614; c) M. L. Clarke, M. B. Díaz-Valenzuela, A. M. Z. Slawin, *Organometallics*, **2007**, *26*, 16-19.
8. a) C. Federsel, A. Boddien, R. Jackstell, R. Jennerjahn, P. J. Dyson, R. Scopelliti, G. Laurenczy, M. Beller, *Angew. Chem. Int. Ed*. **2010**, *49*, 1-6; b) C. Federsel, R. Jackstell, A. Boddien, G. Laurenczy, M. Beller, *ChemSusChem* **2010**, *3*, 1048-1050; c) A. Boddien, F. Grtner, C. Federsel, P. Sponholz, D. Mellmann, R.Jackstell, H. Junge, M. Beller, *Angew. Chem. Int. Ed*. **2011**, *50*, 6411-6414; d) C. Ziebart, C. Federsel, P.Anbarasan, R. Jackstell, W. Baumann, A. Spannenberg, M. Beller, *J. Am. Chem. Soc*. **2012**, *134*, 20701-20704. e) J. Elek, L. Nádasdi, G. Papp, G. Laurenczy, F. Joó, *Appl.Catal. A: Gen.***2003**, *255*, 59-67; f) Á. Kathó, Z. Opre, G. Laurenczy, F. Joó, *J. Mol. Catal. A: Chem*. **2003**, 204–*205*, 143-148.
9. a) P. G. Jessop, T. Ikariya, R. Noyori, *Chem. Rev*. **1995**, *95*, 259-272; b) P. G. Jessop, F. Joó, C.-C. Tai, *Coord. Chem. Rev*. **2004**, *248*, 2425–2442; c) P. G. Jessop, T. Ikariya, R. Noyori, *Nature*, **1994**, *368*, 231-233; d) P. G. Jessop, Y. Hsiao, T. Ikariya, R. Noyori *J. Am. Chem. Soc*. **1994**,*116*, 8851-8852; e) R. Tanaka, M. Yamashita, K. Nozaki, *J. Am. Chem. Soc*. **2009**, *131*, 14168-14169; f) Y. Jiang, B. Schirmer, O. Blacque, T. Fox, S. Grimme, H. Berke, *J. Am. Chem. Soc*. **2013**, *135*, 4088-4102.
10. K. Rajesh, H, Berke, *Adv. Synth. Catal*. **2013**, *355*, 901-906.

Homogeneous Claisen-Tishchenko Reactions of Aldehydes and Transfer Hydrogenation Reactions of Ketones and Imines Catalyzed by Rhenium Complexes

7.1. Introduction

The developments in organometallic chemistry have widely strengthened the concept of homogeneous catalysis and today it can be applied to most of the chemical transformations in industry to serve an increasing demand of the world. The growing concern on environmental conservation focuses chemistry-wise mainly on catalytic strategies. Molecular catalysts offer improved selectivity, increased activity, and allow operationally lower temperatures. Ester synthesis and hydrogenation of organic substrates are among the many fundamental transformations of fine chemical industry. The atom economic Claisen-Tishchenko disproportionation of aldehydes to the corresponding carboxylic esters (Scheme 7.1)[1] has acquired wide attention due to their application in food, polymer, dye and perfume industry.[2] Traditional catalysts for this reaction include mainly sodium[3a-b] and particularly aluminium alkoxides.[3c-g] boric acid,[3h] *i*-Bu_2AlH,[3i] alkaline earth metal amides,[3j,k] $LiBr/Et_3N$,[3l] NaH,[3b,m-n] Grignard reagents in combination with thiolates,[3o] selenide ions[3p] were also reported as catalysts derived from main group elements. Very recently, we reported alkali metal *tert*-butoxides, hydrides and bis(trimethylsilyl)amides as efficient catalysts for this reaction, in which the former two species were realized to be the best known catalysts reported among the class of catalysts derived from main group elements.[4] N-heterocyclic carbenes,[5] transition metal complexes based on Fe,[6a-b] Ru,[6c-h] Rh,[6i-k] Os,[6l] Ir,[6m-n] Ni,[6o-p] Zr,[6q] Hf[6q] and lanthanide

complexes,[7a-g] particularly lanthanide amides[7b-e] and organoactinide complexes[7h-i] have also been employed for this reaction. Recently, this disproportionation reaction between two different selected aldehydes could be accomplished in good selectivities using a metal complex of Ni.[1f,6p]



Scheme 7.1. Claisen-Tishchenko Reaction

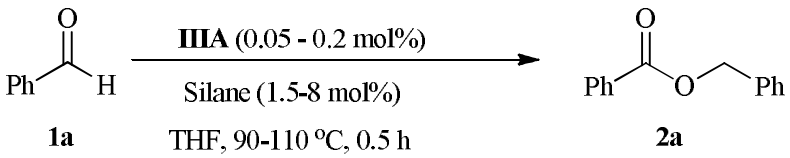
7.2. Claisen-Tishchenko Reaction of Aldehydes Catalysed by IIIA

7.2.1. Results and Discussion

When we started to study the activity of complexes **IIIA**, **IIA**, **VIIA** and **VIIB** in combination with Et_3SiH for the hydrogenation of carbonyl compounds, we came across the formation of benzyl benzoate during the hydrogenation of benzaldehyde (chapter 6). This led us to investigate the scope of this complex as a catalyst in Claisen-Tishchenko type disproportionations. This reaction using the rhenium complex **IIIA** or any of the tested silanes could not give the product. Only the combination of both established catalytic transformations.

The feasibility of the catalytic Claisen-Tishchenko reaction has been studied using benzaldehyde as model substrate with 0.05 mol% of complex **IIIA** along with variable quantities of different organosilanes as co-catalysts in THF at 110 °C (Table 7.1). None of the tested silanes could give complete conversion due to concomitant hydrosilylations in most cases. Also, sterically demanding silanes either did not show any reaction or gave lower yields (Table 7.1, entries 2, 3 and 5). In terms of activity, diphenyl silane (Ph_2SiH_2) was found to be the best choice; using 2.5 mol% showed a TOF of 3280 h^{-1} and 82% GC yield of benzyl benzoate within 0.5 h in 85% conversion (Table 7.1, entry 7). When only 1.5 mol% of

Table 7.1. Claisen-Tishchenko reaction of benzaldehyde using **IIIA**/various silyl hydride system[a]



Entry	Silane/Mol%	TOF (h^{-1})	Yield (%)	Conv. (%)
1	Et_3SiH/2.5	2648	67	70
2	i-Pr_3SiH/2.5	-	-	-
3	$PhMe_2SiH$/2.5	118	30	35
4	$(MeO)_3SiH$/2.5	2360	59	63
5	Ph_3SiH/2.5	-	-	-
6	$PhSiH_3$/2.5	2520	63	66
7	Ph_2SiH_2/2.5	3280	82	85
8	Ph_2SiH_2/1.5	3080	77	79
9	Ph_2SiH_2/(1.5+5)	-	88	94[b]
10	Ph_2SiH_2/8	3360	84	92
11	Ph_2SiH_2/2.5	2453	61	65[c]
12	Ph_2SiH_2/5	1497	75	87[d]

[a]Yield by GC/MS based on the consumption of aldehyde. [b]Reaction run for another 1 h after adding 5 mol% more of Ph_2SiH_2. [c]Reaction was carried out at 90 °C. [d]0.1 mol% of **IIIA** was used.

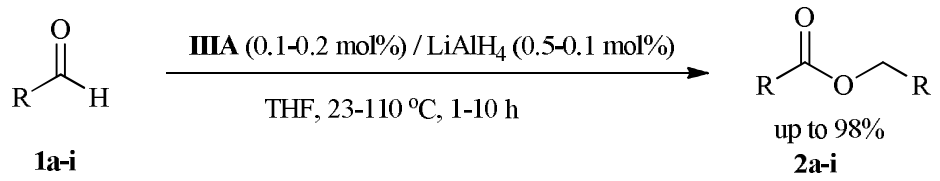
Ph_2SiH_2 was used, a TOF of 3080 h^{-1} was observed with a conversion of 79% giving rise to 77% yield of benzyl benzoate in 0.5 h (Table 7.1, entry 8). Additional 5 mol% of Ph_2SiH_2 was added to this reaction mixture to further advance it giving rise to a yield of 88% of benzyl benzoate with 94% conversion in another 1 h (Table 7.1, entry 9). However, addition of a higher quantity of Ph_2SiH_2 (8 mol%) at the beginning itself gave 84% yield in 92%

conversion within 0.5 h (Table 7.1, entry 10). Lowering the temperature to 90 °C showed a TOF of 2453 h^{-1} with a yield of 61% of benzyl benzoate in 65% conversion (Table 7.1, entry 11). Reaction was then carried out with a double loading of **IIIA** (0**.**1 mol%) along with 5 mol% of Ph_2SiH_2. This gave a TOF of 1497 h^{-1} with a yield of 75% of the product in 87% conversion (Table 7.1, entry 12).

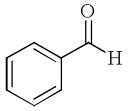
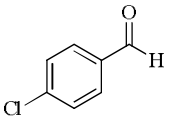
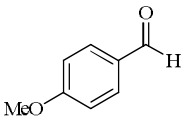
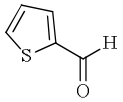
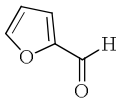
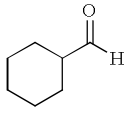
The reaction of **IIIA** or of the mixture of **IIA** and **IIIA** (~ 2:1 obtained after a fresh preparation) with excess of Et_3SiH (20 equiv.) in THF-d_8 at 70 °C gave same mixture of products in both cases, which were stable only in the reaction solution. NMR study revealed the major product as a dihydride silyl rhenium complex (chapter 2). In order to overcome the limitations of incomplete conversion and the formation of undesired side products in the silane co-catalyzed Claisen-Tishchenko reaction of aldehydes, we thought of preparing suitable stable hydride species using other hydride reagents. Thus, the reaction of **IIIA** with 5 equiv. of $LiAlH_4$ in THF at room temperature was probed rise to immediate formation of a mixture of rhenium hydrides analyzed *in situ* by ^1H and ^{31}P NMR spectroscopy. Detailed *in situ* NMR studies revealed one of them to be a rhenium trihydride species **XXXVA** (Scheme 7.2), (^1H NMR, trihydride): δ -5.58 (m, 1H), -3.20; (m, 2H,); other hydride: -9.02 (br, m). However, attempts of isolation of these complexes in the solid state led to formation of mixtures of various other rhenium hydride species as yet not fully characterized.

Then, this *in situ* prepared mixture of rhenium hydrides (obtained by the reaction of **IIIA** with $LiAlH_4$ in THF) were tested for the catalytic Claisen-Tishchenko disproportionation reaction (Table 7.2). With a 0.1 mol% loading of **IIIA** along with 0.5 mol% of $LiAlH_4$, at room temperature, though the disproportionation of benzaldehyde to benzyl benzoate proceeded, it was found to be slow giving rise to a GC yield of < 20% in 12 h (Table 7.2, entry 1). As expected, < 1% of benzyl alcohol was also formed primarily due to

Table 7.2. Claisen-Tishchenko reaction of aldehydes using **IIIA**/$LiAlH_4$ system.[a]



1a-i **2a-i**

Entry	Aldehyde (**1**)		**IIIA**/ mol%	Temp. (°C)	TOF (1^{st} h)	Time (h)	Yield (**2**, %)	Alcohol (%)
1		**1a**	0.1	23	11	12	<20	< 1
2				80	260	10	97	< 1
3		**1b**	0.2	110	275	5	96	< 1
4		**1c**	0.2	110	495	1	99	< 1
5		**1d**	0.2	110	391	3.5	97	< 1
6		**1e**	0.2	110	150	16	90	2
7		**1f**	0.2	23	490	<1	98	< 1
8		**1g**	0.2	23	465	<1	93[b]	< 1
9		**1h**	0.2	23	435	1.5	96	< 1
10		**1i**	0.2	110	121	1	24[b,c]	< 1

[a]Unless mentioned, TOF and yield by GC/MS based on the consumption of aldehydes. [b] yield by ^{1}H NMR spectroscopy using an internal standard; naphthalene for entry 8 and mesitylene for entry 10. [c]Paraformaldehyde was used as the substrate.

the hydrogenation of benzaldehyde by $LiAlH_4$.Under the same loadings, but at a temperature of 80 °C, benzyl benzoate was obtained in 97% GC yield in 10 h with a TOF of 260 h^{-1} for the first hour (Table 7.2, entry 2). It is worth mentioning that similar results were obtained when a mixture of **IIA** and **IIIA** (~ 2:1 obtained immediately after preparation) was used as catalyst instead of only **IIIA**. Without the addition of any substrate, when the *in situ* formed rhenium hydrides (obtained by the reaction of **IIIA** with $LiAlH_4$ in THF) were heated to 80 °C, we observed the disappearance of the trihydride species where the other species remained. Addition of 20 equiv. of benzaldehyde to this solution did not give any benzyl benzoate at room temperature as well as at a temperature of 80 °C indicating the disappeared rhenium trihydride species was responsible for this disproportination reaction. This strategy was adopted for Claisen-Tishchenko disproportionation of a selection of other aromatic and heteroaromatic aldehydes using complex **IIIA** as catalyst, but carried out at a still higher loading of 0.2 mol% of **IIIA** and 1 mol% of $LiAlH_4$ at a temperature of 110 °C (Table 7.2, entries 3-6). The electron rich 4-anisaldehyde showed a TOF of 495 h^{-1} giving rise to 99% yield of the desired ester within an hour (Table 7.2, entry 4). Also, the electron rich heteroaromatic aldehyde, 2-thiophenecarboxaldehyde, gave a yield of 97% of the desired ester in 3.5 h (Table 7.2, entry 5), whereas the electron deficient heteroaromatic aldehyde, 2-furfuraldehyde, which is known to be difficult to undergo the Claisen-Tishchenko reaction[3n,8] gave only 90% yield of the desired ester in 16 h (Table 7.2, entry 6). Then we tested aliphatic primary and secondary aldehydes for this reaction. Unlike aromatic and heteroaromatic aldehydes, these aliphatic aldehydes could be smoothly converted to the corresponding esters at room temperature. The primary aldehyde, hexanal could be disproportionated with a loading of 0.2 mol% of **IIIA** and 1 mol% of $LiAlH_4$ in THF at room temperature to obtain the corresponding ester, hexyl hexanoate, in 98% yield within 1 h showing a TOF of 490 h^{-1} (Table 7.2, entry 7). Under these conditions, the secondary aldehydes, isobutyraldehyde and

cyclohexanecarboxaldehyde gave yields of the corresponding esters in 93% and 96% respectively (Table 7.2, entry 8 and 9). Claisen-Tishchenko disproportionation of paraformaldehyde could also be carried out at a temperature of 110 °C in THF when a catalyst loading of 0.2 mol% and a $LiAlH_4$ loading of 1 mol% was applied leading to the desired ester, methyl formate, in 25% yield in 5 h, as analyzed and quantified by ^{1}H NMR spectroscopy using mesitylene as internal standard (Table 7.2, entry 10).

7.2.2. Mechanistic Studies

Claisen-Tishchenko disproportionations of aldehydes are envisaged to involve the transfer of an aldehydic hydride to the aldehydic carbon of the other aldehyde as the key step. Addition of 20 equiv. of benzaldehyde at room temperature to the mixture containing rhenium trihydride species **XXXVA** led to the disappearence of this trihydride species with the formation of benzyl benzoate and benzyl alcohol as analyzed by ^{1}H NMR. Benzyl alcohol was generated mainly by reduction of benzaldehyde with $LiAlH_4$. The anionic complex **XXXVA** would have underwent dissociation of a hydride ligand there by leaving $LiAlH_2Br_2$ and generating the active species **XXVIIIA** (Scheme 7.2). Also, as discussed, rhenium hydrides could be obtained by the reaction of **IIIA** with Et_3SiH which gave the hydrosilylated benzyltriethylsilyl ether as a by-product of the disproportionation reaction of the benzaldehyde. Presumably due to a too large bite angle of the Sixantphos ligand, the sixantphos hydride complexes were unstable. Thus sixantphos complex analogous to the rhenium hydride complex **VIE** bearing comparatively smaller bite angle 1,1'-bis(diphenylphosphino)ferrocene (dppf; **E**) ligand could not be obtained on the reaction of **IIA** or **IIIA** with Et_3SiH followed by ethylene, it underwent an *ortho*-metallation instead (Chapter 2). Nevertheless, hydrogenolysis of the *ortho*-metallated rhenium carbon bond led to the formation of the 16 e^- rhenium hydride **VA**, the active species for olefin hydrogenations.

The complex **VIE** catalyzed the disproportionation even in the absence of a co-catalyst, but was far less active. These reactions also revealed formation of benzyl alcohol indicating that the reaction may have proceeded via a rhenium alkoxide species. Kinetic studies using the **IIIA**/$LiAlH_4$ system on the disproportionation reaction of hexanal to hexyl hexanoate showed a linear relationship between ln[reactant] and time peaking for a first order dependency with respect to the substrate (Figure 7. 1). Thus, from these observations, one can conclude that the disproportionation reaction of aldehydes by the rhenium hydride system **VIE**, or those formed either by the reaction of **IIIA** with $LiAlH_4$ or silane would expected to pass through a rhenium alkoxide intermediate formed by the hydride transfer to aldehydes or insertion of aldehyde into the rhenium hydride bonds (Scheme 7.2).[6h] Subsequent coordination of a molecule of aldehyde to alkoxide complex followed by insertion into the rhenium alkoxide bond results in the formation of a rhenium hemiacetal species. In the case of the silane co-catalyzed reaction, the coordinated aldehyde and the coordinated silyl group could be in competitive for insertion into the rhenium alkoxide bond or for reductive elimination of the hydrosilylated ether product. The hemiacetal species formed by the insertion of aldehyde into

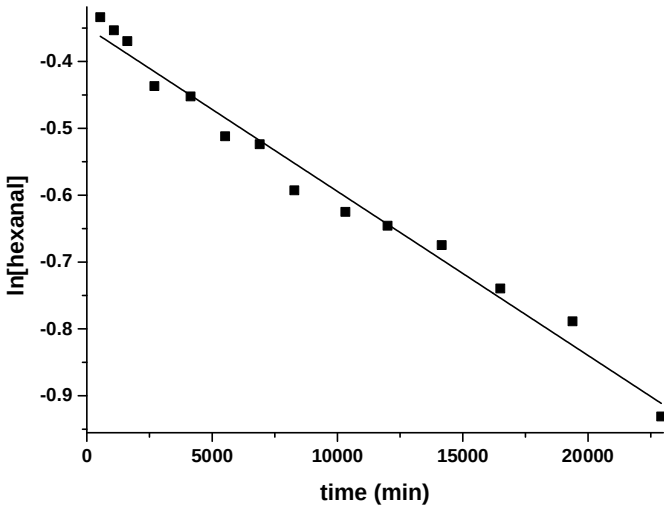
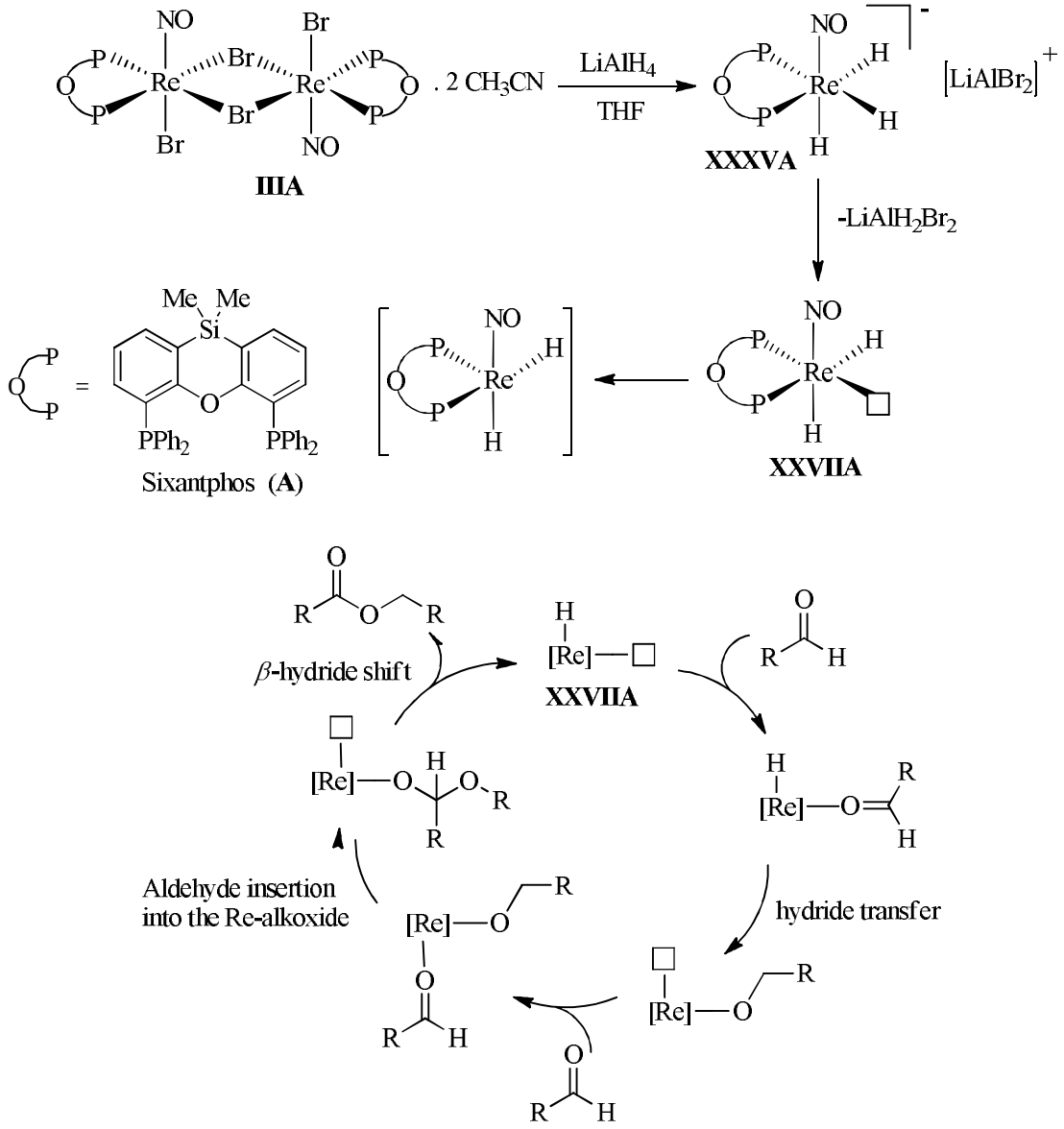


Figure 7. 1. Linear plot of ln[hexanal] *vs* time for the Claisen-Tishchenko reaction using **IIIA**/$LiAlH_4$ system indicating a first order kinetic with respect to hexanal.



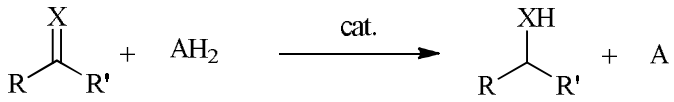
Scheme 7.2. Proposed catalytic cycle for the Claisen-Tishchenko reaction of aldehydes using **IIIA**/$LiAlH_4$ as catalyst.

the rhenium alkoxide bond would eventually undergo β-hydride shift eliminating the ester and regenerating the rhenium hydride species.

7.3. Transfer Hydrogenations of Ketones and Imines

The key step involved in Claisen-Tishchenko reactions is the hydride transfer from one molecule of aldehyde to another molecule of aldehyde and subsequent coupling between the two species. Thus, one can expect that metal complexes capable of performing this

transformation can often also catalyze transfer hydrogenations of polar substrates like aldehydes, ketones and imines (Scheme 7.3). Like catalytic hydrogenation, catalytic transfer hydrogenation is also considered to be an environmentally friendly transformation, the latter even much safer and convenient to handle on any scale. Most of the reported transition metal catalyzed transfer hydrogenation reactions of ketones and imines are designed to operate through Shvo[9,10] or Noyori[9,11] type secondary coordination sphere metal ligand bifunctional mechanisms with simultaneous proton and hydride transfers.[12] On the other hand, primary



$X = O, NR''$; $AH_2 = H_2$ donor, A = H_2 acceptor

Scheme 7.3. General sketch of the transfer hydrogenation reaction

coordination sphere mechanisms operating through the availability of a metal hydride and a vacant site are also reported extensively on ruthenium systems particularly bearing monodentate phosphines.[9,13]

7.3.1. Transfer Hydrogenation of Ketones Catalyzed by IIIA

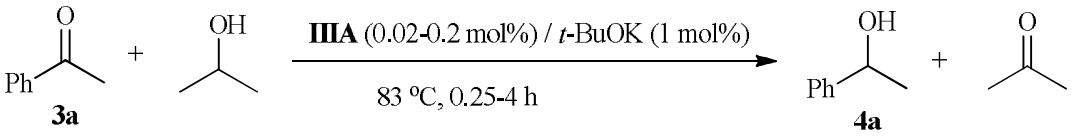
7.3.1.1. Results and Discussion

Since the *in situ* generated rhenium hydrides are active catalysts for the Claisen-Tishchenko reaction, we thought these would also be active catalysts for the transfer hydrogenation of aldehydes, ketones and imines which were in many parts of the catalytic cycles expected to be related. In an exploratory way, transfer hydrogenations of acetophenone were carried out testing different conditions (Table 7.3). Catalysis could not be observed with only **IIIA**. Using **IIIA** in the presence of the silane Ph_2SiH_2 as co-catalyst, the reaction was found to be far less efficient even at higher temperatures when compared to the **IIIA**/$LiAlH_4$ or **IIIA**/base catalytic systems (Table 7.3, entry 1). With loadings of 0.2 mol% of **IIIA** and 1 mol% of

$LiAlH_4$ or *t*-BuOK using 10 equiv. of 2-propanol as the hydrogen donor gave a conversions of only <10% in both cases when run for 12 h at room temperature (Table 7.3, entries 2 and 3). However, when these reactions were carried out at 83 °C, 83% yield of the product 1-phenylethanol was obtained within an hour in both the cases (Table 7.3, entries 4 and 5). The *t*-BuOK co-catalyzed reaction at a further elevated temperature of 110 °C also did not give considerable improvement (Table 7.3, entry 6). With the same loadings at 83 °C, reaction using KOH gave a little less of the product (Table 7.3, entry 7). Still higher loadings of 0.4 mol% of the catalyst and 2 mol% of *t*-BuOK along with 20 equiv. of 2-propanol could give a yield of 89% of the alcohol (Table 7.3, entry 8). However, under any of the above conditions and loadings, no further progress of the reaction was observed. Now, samples were taken in 0.25 h for the transfer hydrogenation of acetophenone; with loadings 0.2 mol% of **IIIA** and 1 mol% *t*-BuOK in 20 equiv. of 2-propanol, which gave 89% of the desired alcohol showing a TOF of 1780 h^{-1} (Table 7.3, entry 10). Thus, the reaction with higher loadings of catalysts (Table 7.3, entry 8) would have achieved this yield within 0.25 h and the other reactions (Table 7.3 entries 4-7 and 9) would have achieved in 0.25 h, yields almost close to those observed in 1 h. This is further concluded from a yield of 81%, obtained when sample was taken for this reaction with loadings of 0.2 mol% **IIIA** and 1 mol% *t*-BuOK (Table 7.3, entry 4). A yield of 89% was obtained even with a loading of only 0.05 mol% of **IIIA** along with 1 mol% of *t*-BuOK with 20 equiv. of 2-propanol in 1 h for which a TOF of 6160 h^{-1} with 77% yield was observed in 0.25 h (Table 7.3, entry 11). When the loading was further reduced to 0.02 mol%, 46% of the alcohol was formed in 0.25 h with a TOF of 9200 h^{-1} giving rise to a yield of 89% of the desired alcohol in 4 h (Table 7.3, entry 12).

Then, this strategy of transfer hydrogenation was tested for various ketones keeping the *t*-BuOK loading as 1 mol% and 2-propanol amount as 20 equiv., but varying the loadings

Table 7.3. Transfer hydrogenation of acetophenone using **2**/additive in 2-propanol.[a]



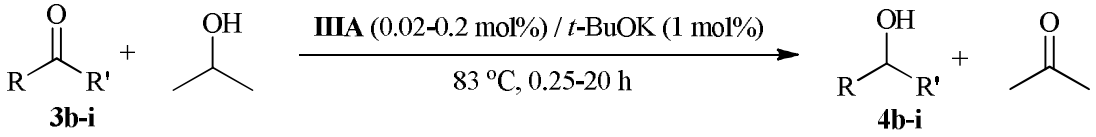
Entry	**IIIA**/ mol%	Additive/mol%	Donor /Equiv.	Temp. (°C)	TOF (h^{-1})	Time (h)	Yield (**4**, %)
1	0.2	Ph_2SiH_2/1	10	100	-	1	<10
2	0.2	$LiAlH_4$/1	10	23	-	1	<10
3	0.2	*t*-BuOK/1	10	23	-	1	<10
4	0.2	*t*-BuOK/1	10	83	1620	0.25	81
					>415	1	83
5	0.2	$LiAlH_4$/1	10	83	>415	1	83
6	0.2	*t*-BuOK/1	10	110	>425	1	85
7	0.2	KOH/1	10	83	>395	1	79
8	0.4	*t*-BuOK/2	10	83	>223	1	89
9	0.2	*t*-BuOK/1	5	83	1460	1	73
10	0.2	*t*-BuOK/1	20	83	>1780	0.25	89
11	0.05	*t*-BuOK/1	20	83	6160	0.25	77
						1	89
12	0.02	*t*-BuOK/1	20	83	9200	0.25	46
						4	89

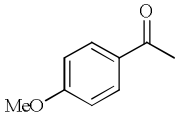
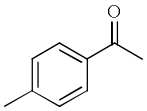
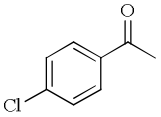
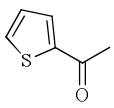
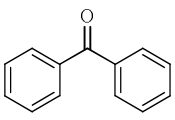
[a]Yield by GC/MS based on the consumption of acetophenone.

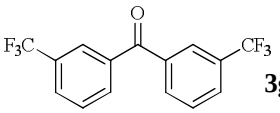
of **IIIA**. Thus, the conditions of 0.02 mol% of **IIIA**, the transfer hydrogenation of 4-methoxyacetophenone showed a TOF of 6191 h^{-1} in the first 0.25 h giving rise to 66% yield of the corresponding alcohol in 10 h (Table 7.4, entry 1). However, the conversion could not

be improved considerably even with a higher loading of 0.2 mol% of **IIIA** (Table 7.4, entry 2). 4-methylacetophenone under the loading of 0.2 mol% showed a TOF of 1529 h^{-1} giving rise to a yield of 82% of the desired alcohol in 1 h (Table 7.4, entry 3). Transfer hydrogenation of 4-chloroacetophenone with 0.05 mol% loading of **IIIA** showed a TOF of 6090 h^{-1} in the first 0.25 h giving rise to a yield of 95% of the corresponding alcohol in < 8 h (Table 7.4, entry 4). With a loading of 0.05 mol%, 2-acetylthiophene showed a TOF of 3568 h^{-1} in the first 0.25 h giving rise to 66% yield of the corresponding alcohol in < 4 h (Table 7.4, entry 5). However, the yield could be improved to only 72% even with a fourfold loading of 0.2 mol% of **IIIA** (Table 7.4, entry 6). Under these conditions, with a loading of 0.02 mol%, the transfer hydrogenation of benzophenone showed a TOF of 3554 h^{-1} in the first 0.25 h giving rise to a yield of 95% of the desired alcohol in 20 h (Table 7.4, entry 7). The transfer hydrogenation of 3,3'- bis(trifluoromethyl)benzophenone was carried out with a loading of 0.2 mol% of **IIIA** showed a TOF of 1060 h^{-1} in the first 0.25 h giving rise to a yield of > 99% yield of the desired alcohol in < 6 h (Table 7.4, entry 8). Attempting transfer hydrogenation of aliphatic ketones, cyclohexanone was used first which with a loading of 0.02 mol% of **IIIA** showed a TOF of 3560 h^{-1} in the first 0.25 h and 99% yield of cyclohexanol in 18 h (Table 7.4, entry 9). The α,β-unsaturated ketone, 2-cyclohexenone, with 0.2 mol% of the catalyst **IIIA** showed in 0.25 h the formation of 41% yield of cyclohexanol, however 51% of the aldol product of cyclohexanone was observed with a conversion of 98%. In order to suppress the aldol formation, *t*-BuOK loading was reduced to 0.2 mol%; thus with 0.05 mol% of **IIIA**, 26% of cyclohexanol, 19% of cyclohexanone, 15% of the aldol products were observed in the first 0.25 h. However, further run of this reaction to 2 h gave a yield of 74% of cyclohexanol, 1% of cyclohexanone and 19% of the aldol products with 99% conversion (Table 7.4, entry 10).

Table 7.4. Transfer hydrogenation of various ketones using **IIIA**/*t*-BuOK in 2-propanol.[a]



Entry	Ketone **3**	**IIIA** (mol%)	TOF (h^{-1})	Time (h)	Yield (%) **4**
1		0.02	6191	0.25	31
			2056	1	41
			328	10	66
2	 **3b**	0.2	1254	0.25	63
			324	1	65
			34	10	68
3	 **3c**	0.2	1529	0.25	76
			403	1	82
4	 **3d**	0.05	6090	0.25	76
			4208	1	84
			239	8	95
5		0.05	3568	0.25	45
	 **3e**			5	66
6		0.2	1309	0.25	65
				4	72
7	 **3f**	0.02	3554	0.25	18
				20	95

8	 **3g**		0.2	1061	0.25	53
				100	4	>99
9		**3h**	0.02	3560	0.25	18
				102	18	99
10[b]		**3i**	0.05	2108	0.25	26[c]
				370	4	74[c]

[a]Yield by GC/MS based on the consumption of substrate. [b]0.2 mol% of *t*-BuOK was used. [c]cyclohexanol.

The failure to improve the reaction even with higher loadings of the catalyst in the case of few of the above reactions can be anticipated to be a consequence of the thermodynamic equilibrium attaining in those reactions.

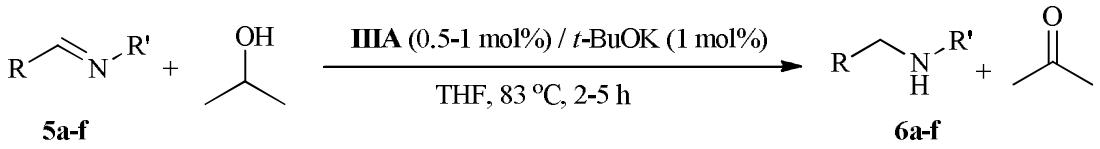
Then the transfer hydrogenation of aldehydes was probed using 4-chlorobenzaldehyde with loadings of 0.05 mol% of **IIIA** and 1 mol% of *t*-BuOK which gave 24% of 4-chlorobenzylalcohol, 34% of the mixed ester isopropyl(4-chlorobenzoate), 8% of the disproportionative ester 4-chlorobenzyl-4-chlorobenzoate and 1% of *t*-butyl(4-chlorobenzoate) with 67% conversion in 24 h. The Claisen-Tishchenko products were anticipated to be formed through separate catalytic cycles operating rhenium alkoxide, as well as potassium alkoxide species.

7.3.2. Transfer Hydrogenation of Imines

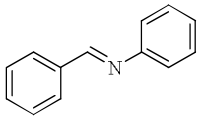
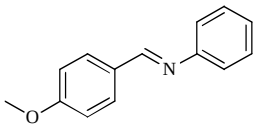
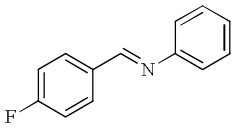
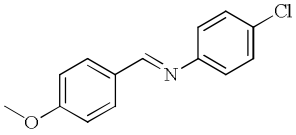
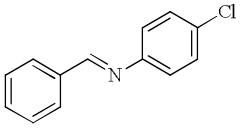
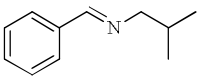
7.3.2.1. Results and Discussion

Pursuing the transfer hydrogenations of imines, the reactions could be brought to near completion for most of the tested imines, but a comparatively higher loading of 0.5 mol% of **IIIA** had to be adopted (Table 7.5). Thus, at 83 °C with 20 equiv. of 2-propanol, the transfer

Table 7.5. Transfer hydrogenation of various imines using **IIIA**/*t*-BuOK in 2-propanol.[a]



5a-f **6a-f**

Entry	Imine **5**		**IIIA**/ mol%	TOF (h^{-1})	Time (h)	Yield (%) **6**
1		**5a**	0.5	136	3	95
2		**5b**	0.5	127	3	89
3		**5c**	0.5	129	3	98
4		**5d**	0.5	170	2	99
5		**5e**	0.5	167	2	95
6		**5f**	1	60	5	48

[a]Yield by GC/MS based on the consumption of imine.

hydrogenation of N-benzylidineaniline showed a TOF of 136 h^{-1} in the first hour giving rise to a yield of 95% of the desired product N-benzylaniline in 3 h (Table 7.5, entry 1). This strategy was also adopted for transfer hydrogenations of other imines. Keeping the other

parameters unchanged, but increasing the loading of catalyst **IIIA** to 1 mol%, N-benzylideneisobutylamine could be converted to the desired product N-benzylisobutylamine with 48% yield in 5 h (Table 7.5, entry 6).

7.3.3. Mechanistic Studies

In order to establish the mechanism of these transfer hydrogenations reaction, labelings as well as kinetic experiments were conducted using benzophenone as a substrate.[9a] As mentioned, the reaction did not give any product when base was not added. **IIIA**, insoluble in benzene-d_6 at room temperature did not show any reaction when 3 equiv. of *t*-BuOK was added, but addition of 5 equiv. of 2-propanol to this mixture showed immediate reaction at this temperature evolving resonances in the ^{1}H and ^{31}P NMR spectra and a by-product identified as acetone. So, the base potassium isopropoxide (*t*-BuOK in 2-propanol) was assumed to have abstracted at least one of the bromides from the rhenium centre of **IIIA** to generate a rhenium isopropoxide species, which had undergone β-hydride abstraction to generate the rhenium hydride species eliminating acetone, as reported for the well known

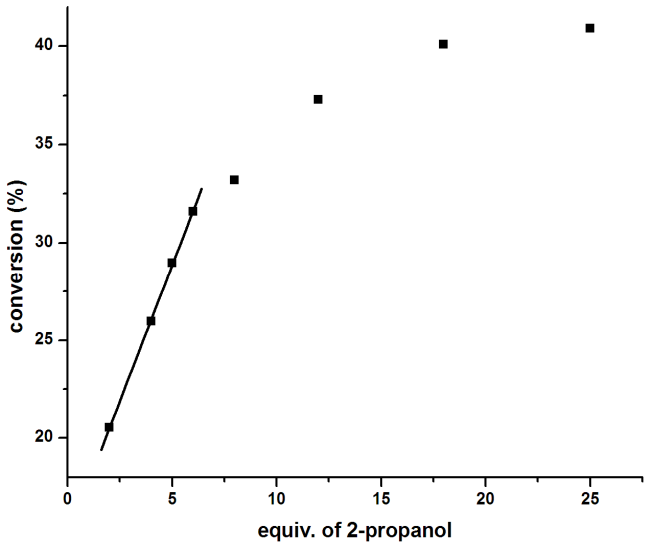
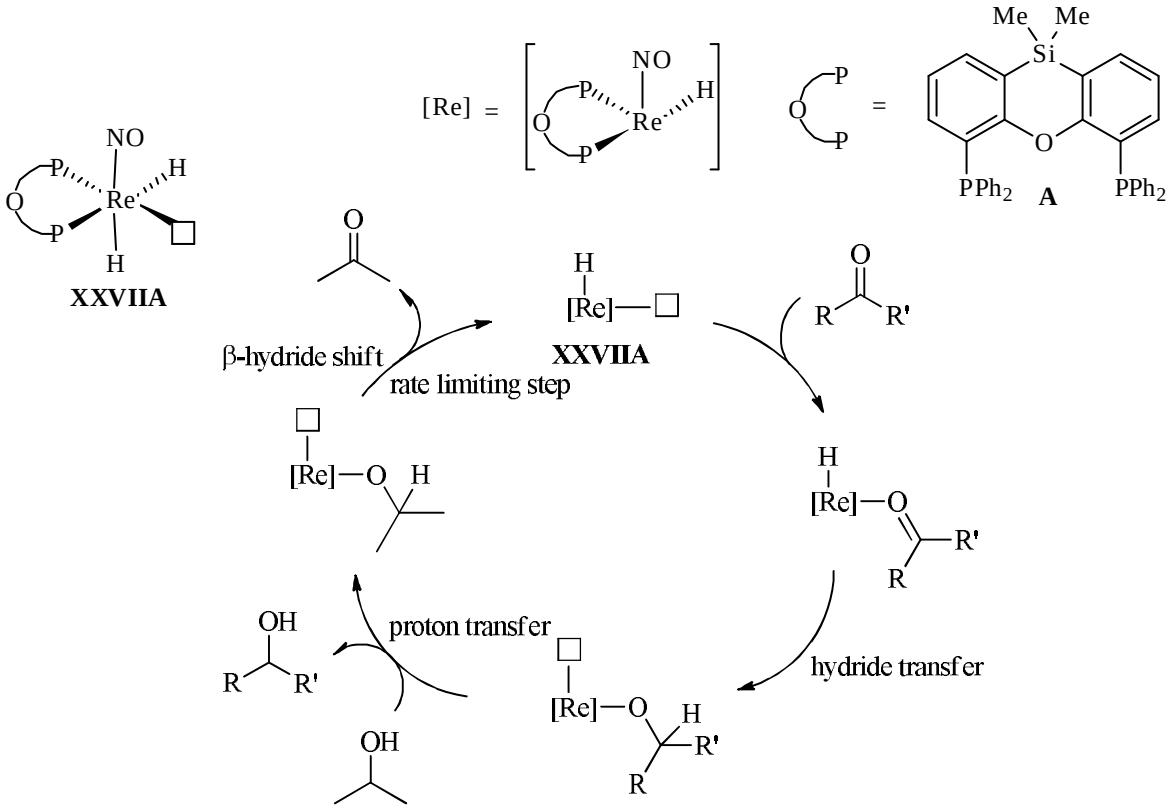
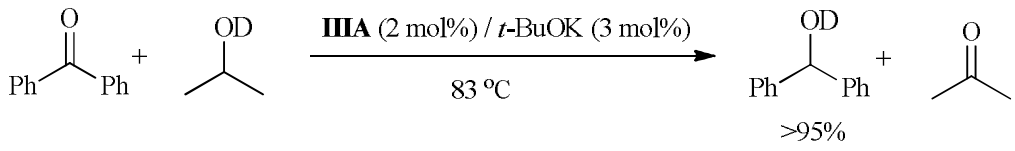


Figure 7. 2. TOF (after 10 min) *vs* concentration 2-propanol on the transfer hydrogenation of benzophenone using **IIIA**/*t*-BuOK system.

hydrogenation of ketones and imines (Scheme 7.4).[9] Evidence for this type of mechanism could be provided from the ability of the rhenium monohydride complex **VIE** alone, which though far much less efficient showed the formation of the desired alcohol. Addition of 1 mol% of *t*-BuOK led to the increase in TOF of this transfer hydrogenation reaction, which could be explained as a consequence of the abstraction of the bromide to generate a rhenium dihydride species.[11b,c] So it is assumed that both the bromides in complex **IIIA** are substituted by the base to form a rhenium dihydride species.



Scheme 7.4. Proposed catalytic cycle for the transfer hydrogenation of ketones using **IIIA**/*t*-BuOK/2-propanol system.



Scheme 7.5. Reaction of benzophenone with $(CH_3)_2CH(OD)$.

The catalytic transfer hydrogenation reaction of benzophenone using $(CH_3)_2CH(OD)$ gave $Ph_2(CH)OD$ (Scheme 7.5) with the content of a label > 95% indicating a reaction in which the hydrides on rhenium are derived from the methyne carbon atoms of 2-propanol ruling out any possibility of an oxidative addition of 2-propanol to the rhenium centre as proposed for $Ru(PPh_3)_3Cl_2$-base co-catalyzed transfer hydrogenations.[11b,c] Coordination of the substrate to the rhenium dihydrides species followed by insertion of it into the Re-H bond would generate a rhenium alkoxide species. It can be concluded that the rhenium alkoxide species is protonated by 2-propanol to form the desired alcohol, there by regenerating the rhenium isopropoxide species. Carrying out the reaction with 0.2 mol% of **IIIA** and 1 mol% of *t*-BuOK, but with 10 equiv. of $(CH_3)_2CH(OH)$, $(CH_3)_2CH(OD)$ and $(CD_3)_2CD(OD)$, a kinetic isotopic effects $K_{HH}/K_{HD}/K_{DD}$ could be established in a ratio of 1:1.35:2.0, respectively at 83 °C when run for 15 min. This revealed that either the β-hydride abstraction or the insertion of the substrate into the Re-H bond (hydride transfer) would be the rate limiting step. At lower concentrations (2-6 equiv.) of 2-propanol, the conversion was found to show a linear dependency which suggested the former to be the rate determining step (Figure

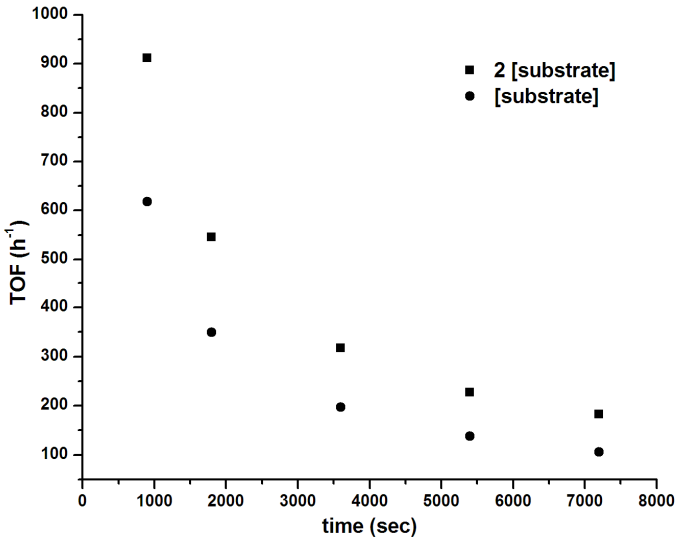


Figure 7.3. TOF (rate) *vs* time for the transfer of hydrogenation of benzophenone at two different concentrations of benzophenopne using **IIIA**/*t*-BuOK/2-propanol system.

7. 2). However at higher concentration of 2-propanol, the increase in conversion became more and more insignificant, presumably due to the saturation of the catalyst with 2-propanol.

Keeping the other parameters the same and increasing the concentration of the substrate, the rate of the reaction also increased. For instance, two experiments with 0.003 mmol of catalyst **IIIA** as the catalyst, 0.015 mmol of *t*-BuOK and 7.5 mmol of 2-propanol, but with 0.75 mmol and 1.50 mmol of benzophenone showed within 0.25 h a TOF of 619 h^{-1} and 912 h^{-1}, respectively. A plot of the TOF *vs* time for these reactions is shown in Figure 7.3.

From the above experiments, it is evident that the reaction follows a first order kinetic with respect to both substrate and 2-propanol. These experiments provided further evidence for this transfer hydrogenation reaction to be operated through a primary coordination sphere mechanism (Scheme 7.5).[9a]

7.4. Conclusion

In conclusion, efficient catalytic Claisen-Tishchenko reaction of formaldehyde, aliphatic aldehydes, as well as aromatic and heteroaromatic aldehydes were realized using a nitrosyl large bite angle Sixantphos rhenium complex along with suitable auxiliary hydrides as co-catalyst. The active species in these transformations is expected to be the corresponding rhenium alkoxide. In addition, mechanistically related efficient transfer hydrogenation of aliphatic, aromatic and heteroaromatic ketones, as well as aromatic and aliphatic imines could be achieved applying the same rhenium catalyst along with a base using 2-propanol as hydrogen donor. A mechanism operative through an inner coordination sphere is proposed for these transfer hydrogenation reactions.

7.5. Experimental Section

All manipulations of addition of reaction components and samplings were done in a glove box filled with dry N_2. All the reagents are purchased from either Aldrich or ABCR chemical company and used without further purification.

General Procedure for the Claisen-Tishchenko Reaction

Complex **IIIA** (3 mg, 0.00296 mmol) and $LiAlH_4$ (0.56 mg, 0.0148 mmol) was taken in a Young Schlenk tube. THF (1 mL) was added to it and shaken for 1 min. To this, the aldehyde (appropriate quantity) was added. The Schlenk was closed and the mixture was stirred (in the glove box at room temperature reactions or kept outside the glove box in an oil bath for heating). The reaction was monitored by GC/MS for which the samples were taken in the glove box, quenched immediately with water outside. The yield was determined by GC/MS analysis based on the consumption the aldehydes.

General Procedure for the Transfer Hydrogenation Reactions of Ketones and Imines

In a N_2 glove box, complex **IIIA** (3 mg, 0.00296 mmol) and *t*-BuOK (1.67 mg, 0.0149 mmol) was taken in a Young Schlenk tube. 2-propanol (20 equiv. with respect to the substrate) was added to it and the resulting mixture was shaken well. To this, the ketone or imine (appropriate quantity) was added. The Schlenk was closed and the mass was heated in an oil bath at 83 °C. The reaction was monitored by GC/MS for which the samples were taken into the glove box, quenched immediately with water outside the glove box. The yield was determined by GC/MS analysis based on the consumption the substrate.

GC/MS (CP-3800 Saturn 2000MS/MS spectrometer, Column: Brechbuhler, ZB-5ms, 30m x 0.25mm x 0.25µm) data (compound: retention time, (mass peak)): **1a**: 3.67 min (m/z = 106); **1b**: 5.05 min (m/z = 140); **1c**: 6.05 min (m/z = 136); **1d**: 3.93 min (m/z = 112); **1e**: 3.96 min (m/z = 112); **1f**: 1.81 min (m/z = 100); **1h**: 3.45 min (m/z = 112); **2a**: 9.61 min (m/z = 112); **2b**: 12.28 min (m/z = 280); **2c**: 14.12 min (m/z = 272); **2d**: 8.32 min (m/z = 224); **2e**: 9.73 min (m/z = 224); **2f**: 6.84 min (m/z = 200); **2h**: 9.20 min (m/z = 224); **3a**: 4.44 min (m/z = 120); **3e**: 4.37 min (m/z = 126); **3f**: 35.51 min (m/z = 182); **3h**: 3.10 min (m/z = 98); **4a**: 4.37 min (m/z = 122); **4e**: 4.67 min (m/z = 128); **4f**: 36.00 min (m/z = 184); **4h**: 3.02 min (m/z = 100); **5a**: 9.05 min (m/z = 181); **5b**: 10.89 min (m/z = 211); **5c**: 8.93 min (m/z = 199); **5d**: 12.56 min (m/z = 245); **5f**: 6.04 min (m/z = 163); **6a**: 9.31 min (m/z = 183); **6b**: 10.97 min (m/z = 213); **6c**: 9.32 min (m/z = 201); **6d**: 12.96 min (m/z = 247); **6e**: 10.84 min (m/z = 217); **6f**: 6.11 min (m/z = 165).

7.6. References

1. a) L. Claisen, *Ber. Dtsch. Chem. Ges.* **1887**, *20*, 646-650; b) W. Tischtschenko, *Chem. Zentralbl.* **1906**, *77*, I, 1309-1311; c) T. Seki, T. Nakajo, M. Onaka, *Chem. Lett.* **2006**, *35*, 824-829; d) M. H. S. A. Hamid, P. A. Slatford, J. M. J. Williams, *Adv. Synth. Catal.* **2007**, *349*, 1555-1575; e) K. Ekoue-Kovi, C. Wolf, *Chem. Eur. J.* **2008**, *14*, 6302-6315; f) W. I. Dzik, L. J. Gooßen, *Angew. Chem. Int. Ed.* 2011, *50*, 11047-11049.
2. a) *Ullmann's Encyclopadia of Industrial Chemistry*, 6th edn., Wiley-VCH, Weinheim, **2002**.

3. a) O.Kamm,W. F. Kamm, *Org. Synth.; Coll. Vol. 1*: **1941**,104; b) F. W. Swamer, C. R. Hauser, *J. Am. Chem. Soc.* **1946**, *68*, 2647-2649; c) W. C. Child, H. Atkins, *J. Am. Chem. Soc*. **1923**, *45*, 3013-3023; d) Y. Ogata, A. Kawasaki, *Tetrahedron* **1969**, *25*, 929-935; e) T. Ooi, T. Miura, K. Takaya, *Tetrahedron Lett.* **1999**, *40*, 7695-7698; f) I. Simpura, V. Nevalainen, *Tetrahedron* **2001**, *57*, 9867-9872; g) T. Ooi, K. Ohmatsu, K. Sasaki, T. Miura, K. Maruoka, *Tetrahedron Lett*. **2003**, *44*, 3191-3193; h) P. R. Stupp, *J. Org. Chem*. **1972**, *38*, 1433-1434; i) Y.-S. Hon, Y.-C. Wong, C.-P. Chang, C.-H. Hsieh, *Tetrahedron* **2007**, *63*, 11325-11340; j) M. R. Crimmin, A. G. M. Barrett, M. S. Hill, P. A. Procopiou, *Org. Lett*. **2007**, *9*, 331-333; k) B. M. Day, N. E. Mansfield, M. P. Coles, P. B. Hitchcock, *Chem. Commun.* **2011**, *47*, 4995-4997; l) M. M. Mojtahedi, E. Akbarzadeh, R. Sharifi, M. S. Abaee, *Org. Lett.* **2007**, *9*, 2791-2793; m) D. C. Waddell, J. Mack, *Green Chem*. **2009**, *11*, 79-82; n) T. Werner, J. Koch, *Eur. J. Org. Chem.* **2010**, 6904-6907; o) L. Cronin, F. Manoni, C. J. O' Connor, S. J. Connon, *Angew. Chem. Int. Ed*. **2010**, *49*, 3045-3048; p) S. P Curran, S. J. Connon, *Org. Lett.* **2012**, *14*, 1074-1077.
4. K. Rajesh. H. Berke, *Adv. Synth. Catal*. **2013**, 355, 901-906.
5. A. Chan, K. A. Scheidt, *J. Am. Chem. Soc*. **2006**, 128, 4558-4559.
6. a) M. Yamashita, Y. Watanabe, T.-A. Mitsudo, Y. Takegami, *Bull. Chem. Soc. Jpn*. **1976**, *49*, 3597-3600; b) M. Yamashita, T. Ohishi, *Appl. Organomet. Chem.* **1993**, *7*, 357-361; c) H. Horino, T. Ito, A. Yamamoto, *Chem. Lett*. **1978**, *7*, 17-20; d) T. Ito, H. Horino, Y. Koshiro, A. Yamamoto, *Bull. Chem. Soc. Jpn*. **1982**, *55*, 504-512; e) N. Menashe, Y. Shvo, *Organometallics* 1991, *10*, 3885-3891; f) V. V. Grushin, H. Alper, *J. Org. Chem*. **1991**, *56*, 5159-5161; g) A. Sorkau, K. Schwarzer, C. Wagner, E. Poetsch, D. Steinborn, *J. Mol. Catal. A* **2004**, *224*, 105-109; h) M.-O. Simon, S. Darses, *Adv. Synth. Catal.* **2010**, *352*, 305-308; i) M. Massoui, D. Beaupére, L. Nadjo, R. Uzan, *J. Organomet. Chem.* **1983**, *259*, 345-308; j) C. Tejel, M. A. Ciriano V. Passarelli, *Chem. Eur. J.* **2011**, *17*, 91-95; k) S. H. Bergens, D. P. Fairlie, B. Bosnich, *Organometallics* **1990**, *9*, 566-571; l) P. Barrio, M. A. Esteruelas, E. Onate, *Organometallics* **2004**, *23*, 1340-1348; m) T. Suzuki, T; Yamada, T. Matsuo, K. Watanabe, T. Katoh, *Synlett* **2005**, 1450-1452; n) T. Suzuki, T. Yamada, K. Watanabe, T. Katoh, *Bioorg. Med. Chem. Lett.* **2005**, *15*, 2583-2585; o) S. Ogoshi, Y. Hoshimoto, M. Ohashi, *Chem. Commun.* **2010**, *46*, 3354-3356; p) Y. Hoshimoto, M. Ohashi, S. Ogoshi, *J. Am. Chem. Soc*. **2011**, *133*, 4668-4671; q) K.-I. Morita, Y. Nishiyama, Y. Ishii, *Organometallics* **1993**, *12*, 3748-3752.
7. a) S. Onozawa, T. Sakakura, M. Tanaka, M. Shiro, *Tetrahedron* **1996**, *52*, 4291-4302; b) H. Berberich, P. W. Roesky, *Angew. Chem. Int. Ed*. **1998**, *37*, 1569-1571; c) G. B. Deacon, A. Gitlits, P. W. Roesky, M. R. Bürgstein, K. C. Lim, B. W. Skelton, A. H. White, *Chem. Eur. J*. **2001**, *7*, 127-138; d) M. R. Burgstein, H. Berberich, P. W. Roesky, *Chem. Eur. J*. **2001**, *7*, 3078-3085; e) A. Zuyls, P. W. Roesky, G. B. Deacon, K. Konstas, P. C. Junk, *Eur. J. Org. Chem.* **2008**, 693-697; f) J.-L. Hsu, J.-M. Fang, *J. Org. Chem*. **2001**, *66*, 8573-8584; g) A. Michrowska, B. List, *Nature Chem*. **2009**, *1*, 225-228; h) T. Andrea, E. Barnea, M. S. Eisen, *J. Am. Chem. Soc*. **2008**, *130*, 2454-2455; i) M. Sharma, T. Andrea, N. J. Brookes, B. F. Yates, M. S. Eisen, *J. Am. Chem. Soc*. **2011**, *133*, 1341-1356.
8. a) T. Seki, K. Akutsu, H. Hattori, *Chem. Commun*. **2001**, 1000-1001.
9. For reviews, see; a) S. E. Clapham, A. Hadzovic, R. H. Morris, *Coord. Chem. Rev*. **2004**, *248*, 2201–2237. b) R. Noyori, S. Hashiguchi, *Acc. Chem. Res*. **1997**, *30*, 97; c) K. Junge, K. Schröder, M. Beller, *Chem.*

Commun. **201**1, *47*, 4849-4859; d) S. Chakraborty, H. Guan, *Dalton Trans*. **2010**, *39*, 7427-7436; e) J. Václavík, P. Šot, B. Vilhanová, J. Pecháček, M. Kuzma, P. Kačer, *Molecules* **2013**, *18*, 6804-6828; f) A. Bartoszewicz, N. Ahlsten, B. Martn-Matute, *Chem. Eur. J*. **2013**, *19*, 7274-7302; g) X. Wu, J. Xiao, in *Hydrogenation and Transfer Hydrogenation in Water, (Metal Catalyzed Reactions in Water)*; **2013**, *44*; h) G. Brieger, T. J. Nestrick, Chem. Rev, **1974**, *74*, 567-580.

10. For selected examples, see; Y. Shvo, D. Czarkie, *J. Organomet. Chem*. **1986**, *315*, C25; b) Y. Blum, D. Czarkie, Y. Rahamim, Y. Shvo, *Organometallics* **1985**, *4*, 1459; c) B. L. Conley, M. K. Pennington-Boggio, E. Boz, T. J. Williams, *Chem. Rev*. **2010**, *110*, 2294; d) C. P. Casey, S. W. Singer, D. R. Powell, R. K. Hayashi, M. Kavana, *J. Am. Chem. Soc*. **200**1, *123*, 1090; e) N. Menashe, Y. Shvo, *Organometallics* **1991**, *10*, 3885; f) N. Menashe, E. Salant, Y. Shvo, *J. Organomet. Chem*. **1996**, *514*, 97; g) C. P. Casey, S. W. Singer, D. R. Powell, R. K. Hayashi, M. Kavana, *J. Am. Chem. Soc*. **2001**, 123, 1090; h) N. Menashe, Y. Shvo, *Organometallics* **1991**, *10*, 3885; i) N. Menashe, E. Salant, Y. Shvo, *J. Organomet. Chem*. **1996**, 514, 97. f) A. Landwehr, B. Dudle, T. Fox, O. Blacque, H. Berke, *Chem Eur. J*, **2012**, *18*, 5701-5714.
11. For selected examples, see; a) S. Hashiguchi, A. Fujii, J. Takehara, T. Ikariya, R. Noyori, *J. Am.Chem. Soc*. **1995**, *117*, 7562; b) J. X. Gao, T. Ikariya, R. Noyori, *Organometallics* **1996**, *15*, 1087; c) T. Ikariya, K. Murata, R. Noyori, *Org. Biomol. Chem*. **2006**, *4*, 393; d) R. Noyori, S. Hashiguchi, *Acc. Chem. Res*. **1997**, *30*, 97.
12. H. Berke, *ChemPhysChem* **2010**, *11*, 1837-1849.
13. a) T. Naota, H. Takaya, S.-I. Murahashi, Chem. Rev. 1998, *98*, 2599; b) O. Pàmies, J.-E. Bäckvall, *Chem. Eur. J*. **2001**, *7*, 5052; c) J.-E. Bäckvall, *J. Organomet. Chem*. **2002**, *652*, 105. d) M. Yamakawa, H. Ito, R. Noyori, *J. Am. Chem. Soc*. **2000**, *122*, 1466. e) S. Gladiali, G. Mestroni, Transit. Met. *Org. Synth*. 1998, *2*, 97; f) J. S. M. Samec, J.-E. Bäckvall, *Chem. Eur. J*. **2002**, *8*, 2955-2961. 14; g) A. Aranyos, G. Csjernyik, K. J. Szabó, J.-E. Bäckvall, *Chem. Commun*. **1999**, 351-352; *ibid*, 2131; h) E. Mizushima, M. Yamaguchi, T. Yamagishi, *J. Mol. Catal. A*: *Chem*. **1999**, *148*, 69; i) C. Vicente, G. B. Shulpin, B. Moreno, S. Sabo-Etienne, B. Chaudret, *J. Mol. Catal. A: Chem*. **1995**, *98*, L5-L8; j) P. A. Chaloner, M.A. Esteruelas, F. Joó, L. A. Oro, in *Homogeneous Hydrogenation* (*Ch. 3*), Kluwer Academic Publishers, Dordrecht, The Netherlands,**1994**; k) E. Mizushima, M. Yamaguchi, T. Yamagishi, *Chem. Lett*. **1997**, 237-238; l) C. Standfest-Hauser, C. Slugovc, K. Mereiter, R. Schmid, K. Kirchner, L. Xiao, W. Weissensteiner *J. Chem. Soc. Dalton Trans*. **2001**, 2989; m) Y. Nishibayashi, I. Takei, S. Uemura, M. Hidai, *Organometallics* **1999**, *18*, 2291; n) P. Dani, T. Karlen, R.A. Gossage, S. Gladiali, G. van Koten, *Angew. Chem. Int. Ed. Engl*. **2000**, *39*, 743. o) G. C. Jia, H. M. Lee, L. D. Williams, *J. Organomet. Chem*. **1997**, *534*, 173; p) H. Yang, M. Alvarez, N. Lugan, R. Mathieu, *J. Chem. Soc. Chem. Commun*. **1995**, 1721; s) M. S. Rahman, P.D. Prince, J.W. Steed, K.K. Hii, *Organometallics* **2002**, *21*, 4927; q) A.C. Benyei, F. Joó, *J. Mol. Catal*. **1990**, *58*, 151; r) A. Caballero, F. A. Jalon, B.R. Manzano, *J. Chem. Soc., Chem. Commun*. **1998**, 1879; s) D. Sellmann, F. Geipel, M. Moll, *Angew. Chem. Int. Ed. Engl*. **2000**, *39*, 561; t) S. Bhaduri, K. Sharma, D. Mukesh, *J. Chem. Soc. Dalton Trans*. **1993**, 1191; u) E.M. Gordon, D.C. Gaba, K. A. Jebber, D.M. Zacharias, *Organometallics* **1993**, 5020; v) C.S. Yi, Z. He, I. A. Guzei, *Organometallics* **2001**, *20*, 3641.

.

Homogeneous Thermocontrolled Chemoselective Transfer Hydrogenations of Nitriles Catalyzed by Rhenium Complexes

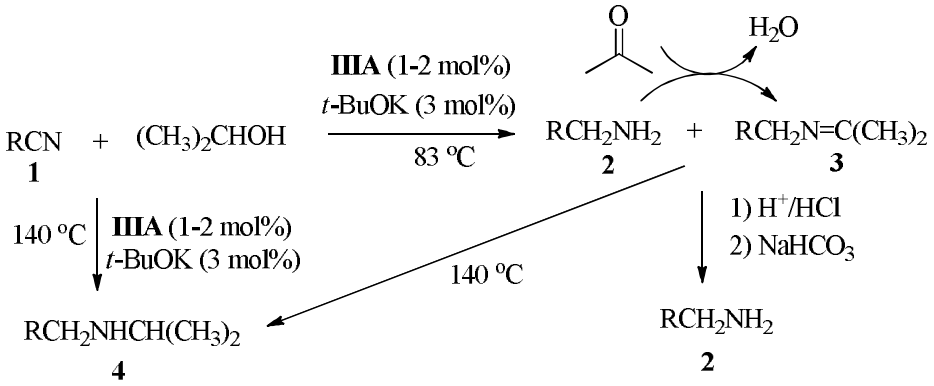
8.1. Introduction

Amines are an important class of compounds constituting organic building blocks and intermediates, in pharmaceuticals, textile, rubber and other agrochemicals as well as in biological processes leading them to be significant in academia and industry.[1] The production of amines are often achieved by catalytic reduction of nitro compounds and imines, amination of alcohols over acidic catalysts, Hydroamination of alkenes, reductive amination of carbonyl compounds, treatment of primary amines with alkyl halides or dialkyl sulfates or sulfonates, addition of nucleophiles or radicals to N-substituted imines.[2] Understanding the mechanism and thereby attempting tuning of the ligand-sphere, catalytic homogeneous hydrogenation and transfer hydrogenation processes are promising tools for the production of a variety of amine compounds. Nitriles are frequently available substrates and the catalytic hydrogenation or transfer hydrogenation of them to produce amines is a challenging difficult process,[3] which is reflected in the very limited number of reports, particularly for the later process for which active systems could be developed only very recently.[4,5] Like catalytic hydrogenation, catalytic transfer hydrogenation is also considered to be an environmentally friendly transformation, the latter even much safer and convenient to handle on any scale. The transfer hydrogenation of nitriles followed by subsequent N-monoalkylation to secondary amines was also reported recently.[6] Like the catalytic hydrogenation of nitriles, the transfer hydrogenation reactions also suffer from selectivity problems (Scheme 8.1).[6]

8.2. Results and Discussion

Transfer Hydrogenation of Nitriles Catalyzed by IIIA

In Chapter 3, we have already discussed the activity of complex **IIIA** for the hydrogenation of nitriles showing selectivity towards secondary or tertiary amines depending on the structure of the nitrile. Also, the ability of this complex to induce transfer hydrogenation reactions of ketones and imines in the presence of suitable bases were also discussed (Chapter 7). We then tested the activity of this complex in transfer hydrogenations of nitriles (Table 8.1). With loadings of 1 mol% of **IIIA** and 3 mol% *t*-BuOK in 25 equiv. of 2-propanol at 60 °C, the transfer hydrogenation of benzonitrile was effected giving a yield of 6% of benzylamine (**2a**) and 58% of N-isopropylidenebenzylamine (**3a**) and < 1% of N-benzylisopropylamine (**4a**) within 12 h of reaction time (Table 8.1, entry 1). N-benzylideneisopropylamine (**3a**) was formed by the condensation reaction between the formed benzylamine (**2a**) and acetone (Scheme 8.1). N-benzylisopropylamine (**4a**) has to be considered a follow-up product of transfer hydrogenation of imine **2a**. This reaction, when carried out at 83 °C, showed the formation of 49% of **2a**, 47% of **3a** (overall 96%; TOF: 384 h^{-1}) and < 1% of **4a** in 0.25 h (Table 8.1, entry 2). **3a** can be considered as the primary amine component since **3a** can be hydrolysed to **2a** in the work up procedure. Thus, the reaction



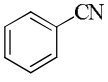
Scheme 8.1. Selective Transfer hydrogenation as well as reductive alkylation of nitriles to amines and N-alkylisopropylamine respectively using **IIIA**/*t*-BuOK/2-propanol system.

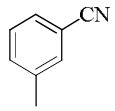
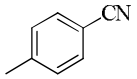
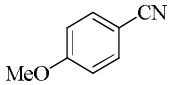
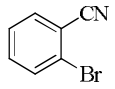
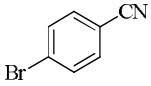
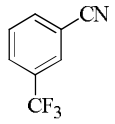
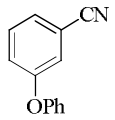
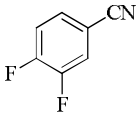
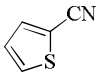
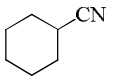
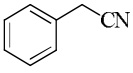
(Table 8.1, entry 2), upon an acid-base work up following purification by column chromatography, furnished 91% yield of benzylamine (**2a)** (Table 8.1, entry 2, in parentheses). Another run of this reaction under the same conditions sampled at 1 h gave 9% of **2a**, 86% of **3a** and 4% of **4a** (Table 8.1, entry 3). Under the same loading of the reaction components, but carried out at a the higher temperature of 140 °C, the reaction furnished the reductively alkylated product **4a** in 93% yield when run for 12 h (Table 8.1, entry 4). Thus, a temperature control can be applied to furnish the desired products of either **2a** or **4a**. In order to exclude the alkylated products, the reaction with 2-butanol was carried out at 100 °C, which did not give any of the desired products, instead 5% of N-benzylidenebenzylamine ($PhCH=NCH_2Ph$) was observed after 1 h.

This transfer hydrogenation strategy using 2-propanol as H_2 donor has been extended to a few more aromatic and aliphatic nitriles (Table 8.1). 3-methylbenzonitrile (**1b**) could be smoothly converted to the corresponding primary amine **2b** and the imine **3b** in yields of 41% and 58% respectively, (overall 99%; TOF: 396 h^{-1}) in 0.25 h when a loading of 1 mol% of **IIIA** was adopted at 83 °C (Table 8.1, entry 5). 4-methylbenzonitrile (**1c**) under these conditions furnished a yield of 36% of primary amine **2c** and 58% of the imine **3c** (overall 94%; TOF: 376 h^{-1}) in 0.25 h (Table 8.1, entry 6). As expected, this reaction after one hour showed a decrease in primary amine **2c** to 9% and an increase in imine **3c** to 87% (overall 96%) (Table 8.1, entry 7). 4-methoxybenzonitrile (**1d**) showed no primary amine **2d**, but furnished 63% of the imine **3d** (TOF: 252 h^{-1}) in 0.25 h when a catalyst loading of 1 mol% was adopted (Table 8.1, entry 8). The absence of this electron rich primary amine **2d** is not surprising, since it is expected that this amine would immediately react with acetone to form the imine **3d**. This reaction gave a yield of 83% of imine **3d** when run for 1 h (Table 8.1, entry 9). When this reaction mixture was heated to 140 °C for 16 h, only 69% of the reductively alkylated product **4d** was obtained, the remains being the imine **3d** (Table 8.1,

entry 10). 2-bromobenzonitrile (**1e**) under the conditions of 1 mol% loading of **IIIA** at 83 °C, furnished 64 % of primary amine **2e** and 34% of imine **3e** (overall 98%) when run for 0.25 h (Table 8.1, entry 11). Under the same conditions, 4-bromobenzonitrile (**1f**) furnished 69 % of primary amine **2f** and 28% of imine **3e** (overall 97%) when run for 0.25 h (Table 8.1, entry 12). However, the reaction mixtures of both 3-(trifluoromethyl)benzonitrile (**1g**) and 3-(phenoxy)benzonitrile (**1h**), after 99% conversion to a mixture of **2g-h** and **3g-h** in 0.25 h (TOF (**2g**+**3g**) and (**2h**+**3h**), both 396 h^{-1}) (Table 8.1, entries 13 and 15) when heated to 140 °C for 16 h furnished the corresponding reductively alkylated products **4g** and **4h,** respectively, in quantitative yield (Table 8.1, entries 14 and 16). A higher loading of 2 mol% of **IIIA** was adopted for the transfer hydrogenation of the electron deficient aromatic nitrile, 3,4-difluorobenzonitrile(**1i**) which gave 72% of **2i** and 24% of **3i** (overall 96%; TOF: 192 h^{-1}) in 0.25 h (Table 8.1, entry 17). Similarly, a loading of 2 mol% of **IIIA** was adopted for the heteroaromatic nitrile, thiophene-2-carbonitrile (**1j**), which furnished 7% of the corresponding primary amine (**2j**) , 83% of the imine (**3j**) (overall 99%; TOF: 83 h^{-1} (first h)) when run for 3 h (Table 8.1, entries 18 and 19). Catalyst loading of 2.5 mol% was adopted for the transfer hydrogenations of the aliphatic nitrile, cyclohexanecarbonirile (**1k**) which showed 5% yield of the primary amine **2k** and 70% yield of the imine **3k** (overall 75%; TOF:

Table 8.1. Transfer hydrogenation of various nitriles catalyzed by **IIIA**/*t*-BuOK/2-propanol system.

Entry	Nitrile **1**	Cat (mol%)	TOF/ $(h^{-1})^a$	Temp/ °C	Time (h)	Yield (%)^b **2/3/4**	Conv. (%)
1	 **1a**	1	-	60	12	6/58/< 1	65
2		1	384	83	0.25	49/47/< 1 (91)	97
3			-	83	1	9/86/4	99
4		1	-	140	16	0/1/93	99

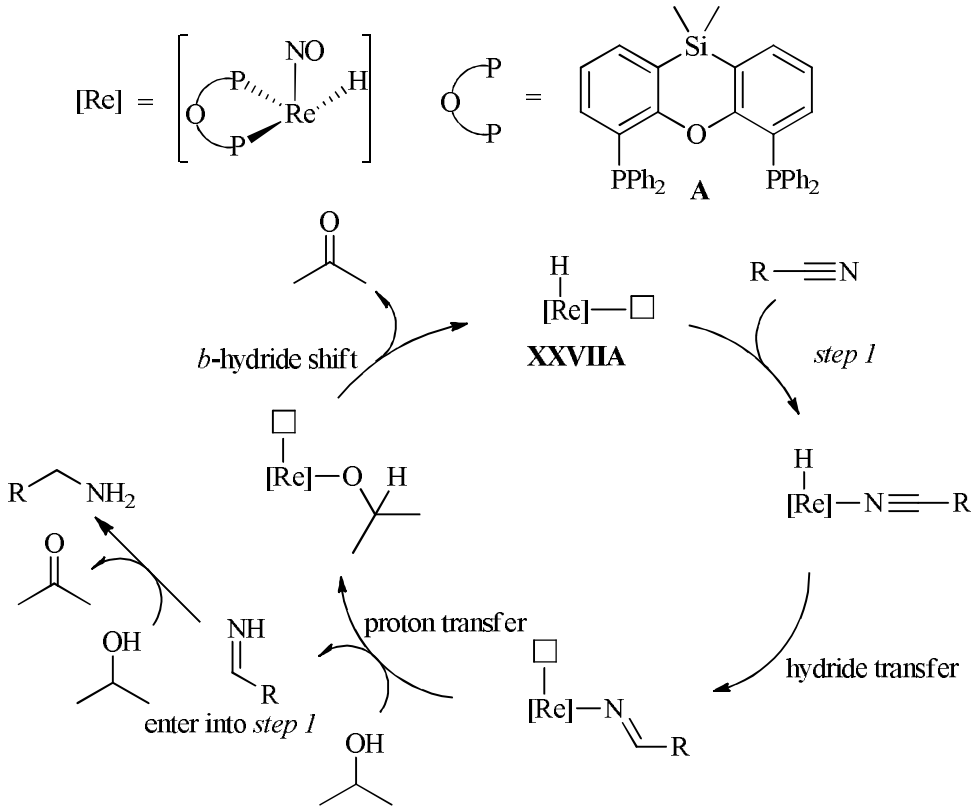
5		**1b**	1	396	83	0.25	41/58/< 1	> 99
6		**1c**	1	376	83	0.25	36/58/0	94
7						1	9/87/1	97
8			1	252	83	0.25	0/63/0	63
9		**1d**		-		1	0/83/2	85
10					140	16	0/31/69	100
11		**1e**	1	392	83	0.25	64/34/0	98
12		**1f**	1	388	83	0.25	69/28/2	> 99
13		**1g**	1	396	83	0.25	63/36/0	99
14					140	16	0/0/> 99	> 99
15		**1h**	1	396	83	0.25	45/54/0	99
16				-	140	16	0/0/> 99	> 99
17		**1i**	2	192	83	0.25	72/24/0	96
18		**1j**	2	98	83	0.25	32/17/0	49
19				-		3	7/83/0	90
20		**1k**	2.5	120	83	0.25	5/70/0	75
21				-		1	9/80/5	94
22		**1l**	2	182	83	0.25	18/67/2	91[d]
23				-		1	5/83/3	95[d]

[a]TOF for the formation of **2** and **3**. [b]Unless mentioned, yield by GC/MS based on the consumption of nitrile. [c]Isolated yield of benzylamine. [d] Remaining being unidentified products.

120 h^{-1}) in 0.25 h (Table 8.1, entry 20). When run for 1 h, the reaction could give rise to **2k** and **3k** in yield of 9% and 80% respectively (overall 89%) (Table 8.1, entry 21). The relatively higher quantity of imine **3k** is attributed to be due to the electron richness of this nitrile 1k, which would enhance the formation of the imine **3k**. As an effect of this higher quantity of the imine **3k**, a relatively higher (5%) yield of the reductive alkylated product was also observed (Table 8.1, entry 21). Under this conditions, but with a loading of 2 mol% of **IIIA**, phenylacetonitrile (**1l**) showed a yield of 18% of the amine **2l** and 67% of the imine 3l (overall 85%; TOF: 182 h^{-1}) in 0.25 h (Table 8.1, entry 22). This reaction run for 1 h could give rise to 5% yield of amine **2l** and 83% yield of the imine **3l** (overall 88%) (Table 8.1, entry 23).

8.3. Mechanistic Aspects

The mechanism of this transfer hydrogenation of nitriles is assumed to be operative through a



Scheme 8.2. Proposed mechanism for the transfer hyfrogenation of nitriles.

catalytic cycle analogous to the one described for transfer hydrogenations of ketones in Chapter 7. The active species is proposed to be the rhenium dihydrides species **XXVIIA** (Scheme 8.2). The aldimine (RCH=NH) generated would further undergo transfer hydrogenation reaction by entering into *step 1* followed by an analogous catalytic cycle, would yield the primary amine (RCH_2NH_2).

8.4. Conclusion

The transfer hydrogenation reactions of a series of aromatic, heteroaromatic and aliphatic nitriles have been realized using **IIIA**/*t*-BuOK/2-propanol system in high yields. Carrying out these reactions at a temperature of 83 °C furnished a mixture of primary amines **2** and N-isopropylidenebenzylamines **3**, the latter can easily be hydrolyzed to the primary amines **2**. Carrying out the transfer hydrogenation reactions at elevated temperature of 140 °C at the beginning itself or after the complete formation of primary amines and N-isopropylaldimines furnished the reductive alkylation products, N-isopropylalkylamines **4** in good to excellent yields. The mechanism of these transfer hydrogenation reactions of nitriles is also proposed.

8.5. Experimetal Section

All manipulations of addition of reaction components and samplings were done in a glove box filled with dry N_2. All the reagents are purchased from either Aldrich or ABCR chemical company and used without further purification.

General Procedure for the Transfer Hydrogenation of Nitriles

Catalyst **IIIA** (0.003 mg, 0.00296 mmol) and *t*-BuOK (0.001 mg, 0.0089 mmol) were taken in a 5 mL Young schlenk flask. To this, benzonitrile (30.5 µL, 0.296 mmol) and 2-propanol (0.57 mL, 0.7.41 mmol) were added. The flask was closed and kept in an oil bath maintained at 83 °C. After appropriate reaction time, the mass was diluted with dichloromethane and analyzed by GC/MS. The yields of the products were determined based on the consumption of nitrile.

For reactions to furnish the reductive alkylated products **4**, either the flask containing the reactants was kept in an oil bath maintained at 140 °C or the reaction mass (after the appropriate time of reaction at 83 °C and sampling) was kept in an oil bath maintained at 140 °C. After appropriate reaction time, the samples were analyzed by GC/MS (CP-3800 Saturn 2000MS/MS spectrometer, Column: Brechbuhler, ZB-5ms, 30m x 0.25mm x 0.25µm) and the yield of the product was determined based on the consumption of the nitrile.

GC/MS data (compound: retention time (mass peak)): **1a**: 3.78 min (m/z = 103); **2a**: 4.00 min (m/z = 107); **3a**: 5.85 min (m/z = 147); **4a**: 5.26 min (m/z = 149); **1b**: 4.66 min (m/z = 117); **2b**: 4.86 min (m/z = 121); **3b**: 6.61 min (m/z = 161); **4b**: 6.02 min (m/z = 163); **1c**: 4.78 min (m/z = 117); **2c**: 4.88 min (m/z = 121); **4b**: 6.68 min (m/z = 161); **4c**: 6.02 min (m/z = 163); **1d**: 6.12 min (m/z = 137); **3d**: 7.77 (m/z = 177); **4d**: 7.22 min (m/z = 179); **1e**: 6.01 min (m/z = 181); **2e**: 6.24 min (m/z = 185); **3e**: 7.72 min (m/z = 225); **1f**: 5.89.02 min (m/z = 181); **2f**: 6.47 min (m/z = 185); **3f**: 8.71 min (m/z = 225); **4f**: 7.56 min (m/z = 227); **1g**: 3.53 min (m/z = 171); **2g**: 4.23 min (m/z = 175); **3g**: 5.81 min (m/z = 215); **4g**: 5.28 min (m/z = 217); **1h**: 9.24 min (m/z = 195); **2h**: 9.62 min (m/z = 199); **3h**: 10.80 min (m/z = 239); **4h**: 10.34 min (m/z = 241); **1i**: 3.47 min (m/z = 139); **2i**: 4.29 (m/z = 143); **3i**: 5.98 min (m/z = 183); **1j**: 3.86 min (m/z = 109); **2j**: 4.03 min (m/z = 113); **3j**: min (m/z = 153); **1k**: 3.75 min (m/z = 109); **2k**: 3.77 min (m/z = 113); **3k**: 5.32 min (m/z = 153); **4k**: 4.98 min (m/z = 155); **1l**: 5.03 min (m/z = 117); **2l**: 4.72 min (m/z = 121); **3l**: 6.21 min (m/z = 161); **4l**: 5.54 min (m/z = 163);

8.6. References

1. For selected reviews and highlights, a) T. E. Müller, M. Beller, *Chem. Rev*. **1998**, *98*, 675-703; b) M. J. Palmer, M. Wills, *Tetrahedron: Asymmetry* **1999**, *10*, 2045-2061; c) J. Seayad, A. Tillack, C. G. Hartung, M. Beller, *Adv. Synth. Catal*. **2002**, *344*, 795-813; d) F. Pohlki, S. Doye, *Chem. Soc. Rev*. **2003**, *32*, 104-114; e) W. Tang, X. Zhang, *Chem. Rev*. **2003**, *103*, 3029; f) H.-U. Blaser, F. Spindler in *Handbook of Homogeneous Hydrogenation*, Vol. 3 (Eds.: J. G. de Vries, C. J. Elsevier), Wiley-VCH, Weinheim, **2007**, pp. 1193; g) R. Severin, S. Doye, *Chem. Soc. Rev*. **2007**, *36*, 1407-1420; h) T. E. M_ller, K. C. Hultzsch, M. Yus, F. Foubelo, M. Tada, *Chem. Soc. Rev*. **2008**, *37*, 3795-3892; i) T. C. Nugent, M. EI-Shazly, *Adv. Synth. Catal*. **2010**, *352*, 753-819; j) M. Rueping, E. Sugiono, F. R. Schoepke, *Synlett* **2010**, 852 -865.
2. a) *Handbook of Homogeneous Hydrogenation*, (Eds.: J. G. de Vries, C. J. Elsevier), Wiley-VCH, Weinheim, **2007**, b) K. S. Hayes, *Appl. Catal. A: Gen*. **2001**, *221*, 187-195. c)A. Seayad, M. Ahmed, H. Klein, R. Jackstell, T. Gross, M. Beller, *Science* **2002**, *297*, 1676-1678.
3. a) R. A. Grey, G. P. Pez, A. Wallo, *J. Am. Chem. Soc*. **1981**, *103*, 7536-7542; b) T. Yoshida, T. Okano, S. Otsuka, *J. Chem. Soc., Chem. Commun.* **1979**, 870-871.
4. a) T. Yoshida, T. Okano, S. Otsuka, *J. Chem. Soc. Chem. Commun*. **1979**, 870-871; b) R. A. Grey, G. P. Pez, A. Wallo, *J. Am. Chem. Soc*. **1981**, *103*, 7536-7545; c) T. Suarez, B. Fontal, *J. Mol. Catal*.

1988, *45*, 335-344; d) C. S. Chin, B. Lee, *Catal. Lett.* **1992**, *14*, 135-140; e) A. M. Joshi, K. S. MacFarlane, B. R. James, P. Frediani in *Progress in Catalysis* (Eds.: K. J. Smith, E. C. Sanford), Elsevier, New York, **1992**, pp. 143-146; f) A. M. Joshi, K. S. MacFarlane, B. R. James, P. Frediani, *Chemical Industries*, Vol. 53, *Catalysis of Organic Reactions*, Dekker, New York, **1992**, 143-146; g) B. Fontal, M. Reyes, T. Surez, F. Bellandi, N. Ruiz, *J. Mol. Catal. A: Chem*. **1999**, *149*, 87-97; h) C. Bianchini, V. Dal Santo, A. Meli, W. Oberhauser, R. Psaro, F. Vizza, *Organometallics* **2000**, *19*, 2433-2444; i) X. Xie, C. L. Liotta, C. A. Eckert, *Ind. Eng. Chem. Res.* **2004**, *43*, 7907-7911; j) T. Li, I. Bergner, F. N. Haque, M. Zimmer-De Iuliis, D. Song, R. Morris, *Organometallics* **2007**, *26*, 5940-5949; k) S. Enthaler, K. Junge, D. Addis, G. Erre, M. Beller, *ChemSusChem* **2008**, *1*, 1006-1010; l) S. Enthaler, D. Addis, K. Junge, G. Erre, M. Beller, *Chem. Eur. J*. **2008**, *14*, 9491-9494; m) D. Addis, S. Enthaler, K. Junge, B. Wendt, M. Beller, *Tetrahedron Lett.* **2009**, 50, 3654-3656; n) R. Reguillo, M. Grellier, N. Vautravers, L. Vendier, S. Sabo-Etienne, *J. Am. Chem. Soc*. **2010**, 132, 7854-7855; o) C. Gunanathan, M. Hçlscher, W. Leitner, *Eur. J. Inorg. Chem*. **2011**, 3381 –3386; p) Dipankar Srimani, Moran Feller, Yehoshoa Ben-David and David Milstein; *Chem. Commun*. **2012**, *48*, 11853-11855.

5. S. Werkmeister, C. Bornschein, K. Junge, M. Beller, *Chem. Eur. J*. 2013, *19*, 4437-4440; b) E. Mizushima, M. Yamaguchi, T. Yamagishi, *J. Mol. Catal. A: Chem*. 1999, *148*, 69–75.
6. X. Cui, Y. Zhang, F. Shi, Y. Deng, *Chem. Eur. J*. **2011**, *17*, 2587-2591; b) S. Werkmeister, C. Bornschein, K. Junge, M. Beller, *Eur. J. Org. Chem.* **2013**, 3671-3674; c

Homogeneous Hydrosilylations of Nitriles Catalyzed by Rhenium Complexes

9.1. Introduction

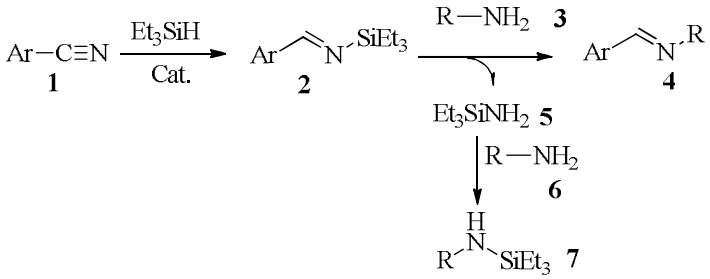
The Nitrile group is one of the most difficult functionality of organic compounds to undergo reduction.[1] The hydrosilylation of nitriles to furnish N-silylaldimines $RCH{=}NSiR'_3$ is a synthetically useful method, but there are only very few catalytic systems documented in literature, which reflect this challenging aspect of 1,2-addition to C≡N bonds.[2] Like the hydrogenation and transfer hydrogenation of nitriles, the hydrosilylation reaction also involves a chemoselectivity issue since the N-silylaldimines, are often much more reactive than nitriles and thus the former would undergo further reactions to give N,N-disilylamines $RCH_2N(SiR'_3)_2$.[2d,3] There are a few reports on stoichiometric hydrosilylation of nitriles.[4] Most of the catalytic reactions reported on the hydrosilylation of nitriles suffer from harsh reaction conditions, very slow rates, low yields and there in almost no reaction for the hydrosilylation of aliphatic nitriles.[5] Nikonov and co-workers have recently documented a promising Ru system operative for chemoselective hydrosilylation of nitriles.[6] However, in any of the reports, the direct synthetic accessibility of the N-silylaldimines could not be established.

9.2. Results and Discussion

9.2.1. Hydrosilylation of Nitriles Catalyzed by IIIA

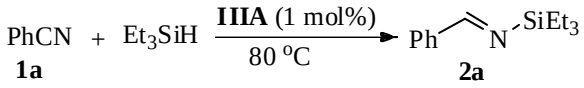
Having encouraged by the ability of the complex **IIIA** to impart catalytic hydrogenations and transfer hydrogenataion of a variety of substrates including nitriles, we

tested the activity of complex **IIIA** for the hydrosilylation of nitriles. With 1 mol% of loading of **IIIA** at 80 °C in THF, the hydrosilylation of benzonitrile was effected using 1.05 equiv. of Et_3SiH giving rise to 79% yield of the monosilylated product N-(triethylsilyl)benzaldimine (**2a**) when run for 1 h (Table 9.1, entry 1) (Scheme 9.1). Under these conditions and run for a period of 1 h, a screening of solvents was carried out. Pentane did not support any reaction; in dichloromethane only 2% of the desired product **2a** was formed. Reactions in the ether, *t*-BuOMe furnished 67% of the product **2a** and that in chlorobenzene led to a yield of 78%.



Scheme 9.1. Hydrosilylation of nitriles and synthetic utility of the formed silylimines for the production of higher imines/amine protection.

Table 9.1. Solvent screening for the hydrosilylation of benzonitrile using Et_3SiH.[a]



Entry	Solvent	Yield[b] (**2**, %)
1	THF	79
2	Pentane	0
3	Dichloromethane	2
4	*t*-BuOMe	67
5	Chlorobenzene	78
6	Toluene	93

[a]1 mol% of complex **IIIA** and 105 mol% of Et_3SiH were used.
[b]By GC/MS based on the consumption of benzonitrile.

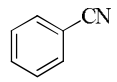
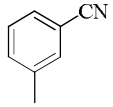
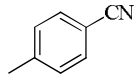
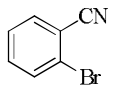
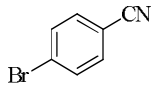
However, toluene was found to the best solvent among the tested ones, which furnished 93% of the desired product **2a**. Continuing this reaction gave 98% yield of **2a** in less than 1.25 h

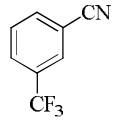
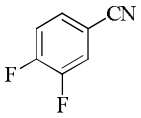
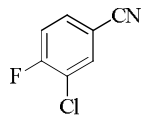
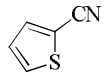
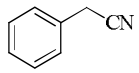
(Table 9.2, entry 1). When carried out with a higher amount of 2.1 equiv. of Et_3SiH, this reaction in toluene gave selectively the monosilylated product **2a** in 99% yield (Table 9.2, entry 3). However, no reaction was observed with $PhSiH_3$, Ph_2SiH_2, Ph_3SiH, $PhMeSiH_2$, Ph_2MeSiH and $(MeO)_3SiH$. At even the higher temperature of 120 °C, the reaction was attempted with Ph_2SiH_2 and $(MeO)_3SiH$, but no reaction was found to proceed.

To underline the generality of the hydrosilylation reaction using **IIIA** as a catalyst, a variety of nitriles were tested with Et_3SiH (1.05 equiv.) in toluene, most of which could give excellent yields when carried out at a temperature of °C. N-(triethylsilyl)benzaldimine (**2a**), obtained by the hydrosilylation of benonitrile with a yield of 78% (TOF of 98 h^{-1}) (Table 9.2, entry 1), upon addition of 1 equiv. of benzylamine **3** (R = $PhCH_2$) (Scheme 9.1) at room temperature immediately furnished the imine N-benzylidinebenzylamine **4** (Ar = Ph, R = $PhCH_2$) in quantitative yield with respect to **2a** or 98% yield with respect to **1a** (Table 9.2, entry 2). The other product of this type of reaction was found to be triethylsilylamine (Et_3SiNH_2) (**5**). **5** was found to react with primary amines to form N-(triethylsilyl)amines (**7**) in as reflected in the addition of more than one equiv. of benzylamine in the hydrosilylation reaction of 3-toluonitrile (**1b**) (Table 9.2, entries 5 and 6), furnishing **7** in 56% yield (with respect to **2b**) (Table 9.2, entry 6). Under the optimized conditions, both 3-tolunitrile (**1b**) and 4-tolunitrile (**1c**) furnished 98% yield of the desired products **2b** and **2c** with a TOF of 78 h^{-1} and 65 h^{-1} respectively (Table 9.2, entries 4 and 7). 2-bromobenzonitrile (**1d**) showed under these conditions a TOF of 65 h^{-1} giving 98% yield of the desired product **2d** (Table 9.2, entry 8) where as 4-bromobenzonitrile (**1e**) required a comparatively higher loading of 2 mol% of **IIIA** furnishing 97% yield of the desired product **2e** within 1.5 h (Table 9.2, entry 10). The electron deficient 3-trifluoromethylbenzonitrile (**1f**) could give a yield of only 42% of **2f** in 5 h when a loading of 2 mol% of **IIIA** was adopted (Table 9.2, entry 11). However, under the

optimized conditions, both 3,4-difluorobenzonitrile (**1g**) and 3-chloro-4-fluorobenzonitrile (**1h**) could be smoothly converted to their corresponding N-silylaldimines **2g** and **2h** in yields of 98% and 95% in 1 h and 1.25 h, respectively (TOF: 98 h^{-1} (**2g**); 66 h^{-1} (**2h**)) (Table 9.2, entries 12 and 15). The strategy of amine additions were tested also for these reactions. The reaction mixture containing **2g** upon addition of one equiv. of benzylamine **3** gave rise to the imine **4g** (Ar = 3,4-difluorophenyl, R = $PhCH_2$) in 43% yield (with respect to **2g**) at room temperature (Table 9.2, entry 13). This upon addition of one more equiv. of benzylamine furnished 98% of the imine **4g** (with respect to 1g) along with 79% of N-(triethylsilyl)benzylamine (**7)** (with respect to **2g**) (Table 9.2, entry 14). When 2 equiv. of aniline was added to the reaction mixture containing **2h**, a 95% yield of the imine **4h** and

Table 9.2. Hydrosilylation of various nitriles with Et_3SiH and subsequent reaction of the formed *N-silylaldimines*[a]

Entry	Nitrile **1**	**IIIA** (mol%)	TOF/ (h^{-1})[a]	Time (h)	Yield (%)	Conv. (%)
1	 **1a**	1	78	1.25	98	98
2			+ $PhCH_2NH_2$		98 (**4a**)	-
3		1	79	1.25	99	99[b]
4	 **1b**	1	65	1.5	98	98
5			+ $PhCH_2NH_2$		98 (**4b**)	-
6			+ $PhCH_2NH_2$		56 (**7**)	-
7	 **1c**	1	78	1.25	98	98
8	 **1d**	1	65	1.5	98	98
9	 **1e**	1	12	5	58	58
10		2	32	1.5	97	97

11		**1f**	2	4	5	42	68[c]
12		**1g**	1	98	1	98	98
13				+ $PhCH_2NH_2$		43 (**4g**)	-
14				+ $PhCH_2NH_2$		98 (**4g**), 79 (**7**)	-
15		**1h**	1	66	1.25	95	99[c]
16				+ 2 $PhNH_2$		95 (**4h**), 79 (**7**)	-
17		**1i**	2	2	2	88	98[c]
18		**1j**	2	8	2	33	41[c,d]

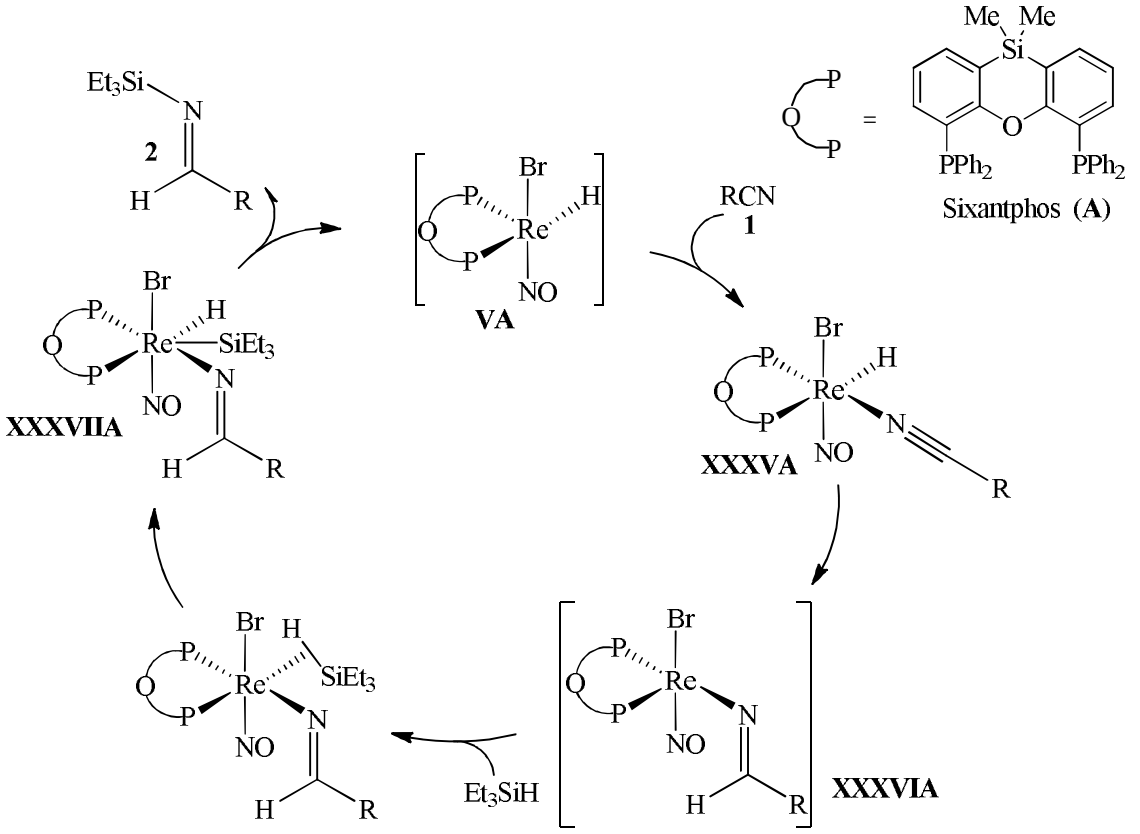
[a]All reactions were carried out in toluene, yield by GC/MS based on the consumption of benzonitrile. [b]Reaction with 2.1 equiv. of Et_3SiH. [c]Remaining being unidentified product(s).[d]Reaction was carriedout at 120 °C.

79% yield of **7** were obtained (Table 9.2, entry 16). A loading of 2 mol% of **IIIA** was adopted for the hydrosilylation of the heteroaromatic nitrile, 2-thiophenecarbonitrile (**1i**) showed a TOF of 22 h^{-1} giving rise to 88% yield of the desired N-silylaldimine **2i** within 2 h (Table 9.2, entry 17). However, under these conditions, the aliphatic nitrile phenylacetonitrile (**1j**) could give only 33% yield of the desired N-silylialdmine **2j** in 2 h (Table 9.2, entry 18).

9.3. Mechanistic Aspects

It was already discussed in Chapter 2 that the species **VA** can be obtained via the reaction of **IIIA** with Et_3SiH. It is a well known fact that the role of R_3SiH in hydrosilylations is related to the role of H_2 in hydrogenations. Therefore, we anticipated a mechanism of the hydrosilylation of nitriles similar to the one proposed for the hydrogenation of olefins.

Primary coordination of nitrile to the coordinatively unsaturated species **V** (Scheme 9.2) would generate the 18e species **XXXVA**. In a *cis* addition mode *β*-hydride transfer occurs to give the coordinatively unsaturated species **XXXVIA**. Coordination of Et_3SiH, followed by oxidative addition of it, would generate the Re(III) species **XXXVIIA**. This would then upon reductive elimination of the product **2** would regenerate the active species **VA**.



Scheme 9.2. Proposed mechanism of hydrosilylation of nitriles catalyzed by **IIIA**.

9.4. Conclusion

Efficient catalytic hydrosilylation of aromatic nitriles using Et_3SiH could be realized applying catalyst **IIIA**. TOFs of up to 98 h^{-1} were achieved at 80 °C with almost equimolar ratios of nitriles and Et_3SiH as starting materials. Only mono hydrosilylation was observed even when 2.1 equiv. of Et_3SiH was present. The hydrosilylation reaction of aliphatic nitriles was not as efficient as that of aromatic nitriles. For the first time, the synthetic utility of a hydrosilylation

reaction could be demonstrated. This produced N-benzylidineamines, R_3SiNH_2 and N-silylamines in a one-pot fashion. Though a variety of compounds including amino acids can be synthesized by the application of nucleophilic addition to N-silylaldimines, the literature in this area is scarce mainly due to the difficult synthetic accessibility of N-silylaldimines.[7]

9.5. Experimental Section

All operations were done in a glove box filled with dry N_2 gas. Only the properly clsed reaction vessels were kept outside in an oil bath at the temperature mentioned.

General Procedure for the Hydrosilylation of Nitriles

Catalyst **IIIA** (0.003 mg, 0.00198 mmol) was weighed into a 5 mL Young schlenk flask. Benzonitrile (20.4 µL, 0.198 mmol) and Et_3SiH (20.7 µL, 0.31 mmol) were added to it using a micro pipette. Toluene (0.5 mL) was added to it. The flask was closed and kept in an oil bath maintained at 80 °C. After appropriate reaction time, the mass was diluted with dry dichloromethane and analyzed by GC/MS. The yields of the products were determined based on the consumption of nitrile.

Procedure for the Subsequent Addition of Amines

The amines were directly added at room temperature to the reaction mass obtained after hydrosilylation reactions. All the products were analyzed by GC/MS and yields were calculated based on the hydrosilylated product.

GC/MS Data: **1a**: 3.79 min (m/z = 103); Et_3SiH: 2.99 min (m/z = 116); Benzylamine: 4.02 min (m/z = 107); Aniline: 3.70 min (m/z: 93); Et_3SiNH_2 (**5**): 2.80 min (m/z (-EtH): 102); **2a**: 8.06 min (m/z = 219); **4a**: 9.46 min (m/z = 195); **7** (R = Ph): 7.77 min (m/z = 207); **7** (R = $PhCH_2$): 8.08 min (m/z = 221); **1b**: 4.64 min (m/z = 117); **2b**: 8.67 min (m/z = 233); **1c**: 4.76 min (m/z = 117); **2c**: min (m/z = 233); **1d**: 6.24 min (m/z = 181); **2d**: 9.56 min (m/z = 299); **1e**: 5.89 min (m/z = 181); **2e**: 9.91 min (m/z = 299); **1f**: 3.52 min (m/z = 171); **2f**: 3.79 min (m/z = 287); **1g**: 3.47 min (m/z = 137); **2g**: 7.93 min (m/z = 255); **1h**: 4.91 min (m/z = 155); **1a**: 9.18 min (m/z = 271); **1i**: 3.86 min (m/z = 109); **1i**: 8.20 min (m/z = 225); **1j**: 5.01 min (m/z = 117); **1i**: 9.79 min (m/z = 181).

9.6. References

1. a) R. A. Grey, G. P. Pez, A. Wallo, *J. Am. Chem. Soc.* **1981**, *103*, 7536-7542; b) T. Yoshida, T. Okano, S. Otsuka, *J. Chem. Soc., Chem. Commun.* **1979**, 870-871

2. a) I. Ojima in *The Chemistry of Organic Silicon Compounds* (Eds.: S. Patai, Z. Rappoport), Wiley, New York, **1989**, ch. 25. b) R. Calas, *Pure Appl. Chem*. **1966**, *13*, 61; c) A. J. Chalk, *J. Organomet. Chem*. **1970**, *21*, 207; d) R. J. P. Corriu, J. J. E. Moreau, M. Pataud-Sat, *J. Organomet. Chem.* **1982**, *228*, 301; e) B. Marciniec, Comprehensive Handbook on Hydrosilylation, Pergamon, Oxford, **1992**.
3. a) T. Murai, T. Sakane, S. Kato, *J. Org. Chem*. **1990**, *55*, 449-453; b) T. Murai, T. Sakane, S. Kato, *Tetrahedron Lett.* **1985**, *26*, 5145-5148; c) A. M. Caporusso, N. Panziera, P. Petrici, E. Pitzalis, P. Salvadori, G. Vitulli, G. Martra, *J. Mol. Catal. A* **1999**, 150, 275-285.
4. a) J. Kim, Y. Kang, J. Lee, Y. K. Kong, M. S. Gong, S. O. Kang, J. Ko, Organometallics 2001, 20, 937; b) M. Tanabe, K. Osakada, *Organometallics* **2001**, *20*, 2118; c) H. Hashimoto, I. Aratani, C. Kabuto, M. Kira, Organometallics **2003**, *22*, 2199; d) T. Watanabe, H. Hashimoto, H. Tobita, J. Am. Chem. Soc. **2007**, *128*, 2176; e) M. Ochiai, H. Hashimoto, H. Tobita, *Angew. Chem. Int. Ed.* **2007**, *46*, 8192.
5 a) A. Y. Khalimon, R. Simionescu, L. G. Kuzmina, J. A. K. Howard, G. I. Nikonov, *Angew. Chem. Int. Ed.* **2008**, *47*, 7701; b) E. Peterson, A. Y. Khalimon, R. Simionescu, L. G. Kuzmina, J. A. K. Howard, G. I. Nikonov, *J. Am. Chem. Soc*. **2009**, *131*, 908.
6. D. V. Gutsulyak, G. I. Nikonov, *Angew. Chem.* **2010**, *122*, 7715-7718.
7. a) G. Cainelli, M. Panunzio, P. Andreoli, G. Martelli, G. Spunta, D. Giacomini, E. Bandini, *Pure Appl. Chem.* **1990**, *62*, 605-612; b) S. Itsuno, M. Sasaki, S. Kuroda, K. Ito, *Tetrahedron: Asymmetry*. **1995**, *6*, 1507-1510); G. Cainelli, D. Giacomini, E. Mezzina, M. Panunzio, P. Zarantonello, *Tetrahedron Lett.* **1991**, *32*, 2967-2970.

DOI: 10.1002/adsc.201200970

Alkali Metal *tert*-Butoxides, Hydrides and Bis(trimethylsilyl)amides as Efficient Homogeneous Catalysts for Claisen–Tishchenko Reaction

Kunjanpillai Rajesh[a] and Heinz Berke[a,*]

[a] Institute of Inorganic Chemistry, University of Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland
Fax(+41)-1-635-6802
E-mail: hberke@aci.uzh.ch

Received: November 3, 2012; Published online: March 15, 2013

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.201200970.

Abstract: Shelf-available alkali metal *tert*-butoxides, hydrides and bis(trimethylsilyl)amides were shown to be highly efficient homogeneous precatalysts for the disproportionation of aldehydes to the corresponding carboxylic esters. Potassium compounds in combination with 18-crown-6 ether could drastically increase the rate of reaction in a few cases. Alternatively, efficient aldol condensations were found for aldehydes possessing an enolizable methylene group at the α-position to the aldehyde functionality. The active species involved in this esterification using any of these alkali metal catalysts is expected to be the metal alkoxide. Potassium compounds were found to be much more efficient when compared to analogous sodium compounds and kinetic studies revealed the rate-determining step to be a second order concerted hydride transfer from a potassium hemiacetal species to another molecule of aldehyde.

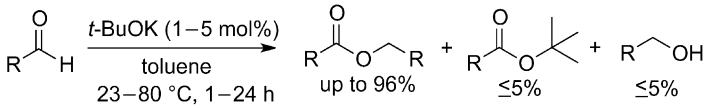
Keywords: aldehydes; alkali metal compounds; Claisen–Tishchenko reaction; crown ethers; esters

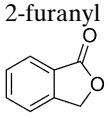
Simple, efficient and environmentally friendly transformations are challenging goals in chemical synthesis. The greatest achievements in these respects have evoked from the concept of catalysis. Featuring high atom economy, the dimerization or disproportionation of aldehydes to the corresponding carboxylic esters, named Claisen–Tishchenko[1] reaction (Scheme 1), has attracted wide attention for the last century and is applied in the food, polymer, dye and perfume industry as well as for the production of ethyl acetate.[2] A number of compounds of the main group elements,[3] transition metal[4] and rare earth[5] compounds, as well as N-heterocyclic carbenes[6] are found to be active to catalyze this reaction. Traditional catalysts for this process include mainly sodium[3a,b] and in particularly aluminium[3c–g] alkoxides. Boric acid,[3h] $(i\text{-Bu})_2AlH$,[3i] alkaline earth metal amides,[3j,k] $LiBr/Et_3N$,[3l] NaH,[3b,m,n] Grignard reagents in combination with thiolates,[3o], selenide ions,[3p] transition metal complexes based on Fe,[4a,b] Ru,[4c–h] Rh,[4i–k] Os,[4l] Ir,[4m,n] Ni,[4o,p] Zr,[4q] Hf[4q] and lanthanide complexes,[5a–g] particularly lanthanide amides,[5b–e] and organoactinide complexes[5h,i] have also been employed for this reaction. Quite recently, this disproportionation reaction between two different selected aldehydes could be accomplished to a certain extent.[1f,4p] However, many of these auxiliaries are toxic, not commercially available or expensive, suffer from low reaction rates, require high catalyst loadings, are air- and moisture-sensitive, undergo side reactions, react sluggishly and are inefficient for heteroaromatic aldehydes, which are known to be difficult to disproportionate to esters.[3n,7]

Scheme 1. The Claisen–Tishchenko reaction.

Recently, we have reported rhenium complexes as precatalysts for the hydrogenation of various olefins[8] and nitriles.[9] Later, when we started to study the activity of one of these complexes in combination with *t*-BuOK for the catalytic hydrogenation of benzaldehyde using H_2, we came across the formation of benzyl benzoate as a by-product. Although the rhenium hydrides generating during this reaction are capable of catalyzing this disproportionative esterification, we found that the simple, inexpensive and commercially available *t*-BuOK itself is an efficient catalyst for this reaction. Much to our surprise and to the best of knowledge, this reaction using *t*-BuOK as catalyst has not been recognized or documented so far.

Table 1. Claisen–Tishchenko reaction catalyzed by *t*-BuOK.



Entry	Product Ester [R][a]	Cat. [mol%]	Temp. [°C]	TOF [1st h][b] [h^{-1}]	Time [h]	Yield[c] [%]
1	phenyl	1	23	81	1.5	96
2	4-chlorophenyl	2	23	29	18	94
3	4-chlorophenyl	2	80	48	1	94
4	2-chlorophenyl	2	23	6	24	92
5	4-bromophenyl	2	23	42	1.5	93
6	4-fluorophenyl	5	80	17	1	80
7	4-methoxyphenyl	2	23	8	24	92
8	2-thienyl	2	23	7	24	88
9	2-furanyl	5	80	15	1.5	79
10[d]		5	80	14	1.5	77

[a] R for entries 1–9.
[b] By GC/MS based on the consumption of aldehyde.
[c] Isolated yield.
[d] *o*-Phthalaldehyde was used as the starting material.

Table 2. Claisen–Tishchenko reaction catalyzed by alkali metal catalysts.

Entry	Product Ester [R]	Cat./[mol%]	Temp. [°C]	TOF [1st h][a] [h^{-1}]	Time [h]	Yield[b] [%]
1	phenyl	*t*-BuONa/5	23	6	9	86
2		$Li[N(SiMe_3)_2]$/5	23	–	90	<5[a]
3		$Na[N(SiMe_3)_2]$/5	23	4	60	85
4		$K[N(SiMe_3)_2]$/5	23	15	7	86
5		$Na[N(SiMe_3)_2]$/2.5	60	22	12	88
6		$K[N(SiMe_3)_2]$/2.5	60	31	2	90
7		KH/1	23	84	1.3	97
8		KH/1	23	98	1	97[c]
9	4-fluorophenyl	KH/5	80	17	1	84
10	4-chlorophenyl	$K[N(SiMe_3)_2]$/5	60	13	2	86
11	4-bromophenyl	$K[N(SiMe_3)_2]$/3	60	21	2	85
12	2-furanyl	KH/5	80	16	1.2	83
13	*tert*-butyl	KH/5	23	14	2	93[d]

[a] By GC/MS based on the consumption of aldehyde.
[b] Unless mentioned, all reactions were carried out in toluene; isolated yield.
[c] The reaction was carried out without a solvent.
[d] Solvent: benzene; yield by ^1H NMR spectroscopy using mesitylene as internal standard.

Using 1 mol% of *t*-BuOK, benzaldehyde could be disproportionated to benzyl benzoate in 1.5 h at room temperature in toluene with a TOF of 81 h^{-1} in the first hour giving 98% GC yield of benzyl benzoate along with 1% benzyl alcohol and 1% *tert*-butyl benzoate. This gave an isolated yield of 96% of benzyl benzoate (Table 1, entry 1). To test whether the catalysis is due to other metal contaminants, we tested 99.99% sublimed grade (trace metals basis) of *t*-BuOK which showed almost the same results. *t*-BuONa was also found to be active for this reaction, but was far less efficient. In the disproportionation of benzaldehyde, reaction with 5 mol% of *t*-BuONa at room temperature showed a TOF of 6 h^{-1} in the first hour giving rise to 86% yield of benzyl benzoate in 9 h (Table 2, entry 1). The scope of the *t*-BuOK-catalyzed reaction has been tested with various aromatic and heteroaromatic substrates (Table 1). The TOF of the reaction could be increased by carrying it out at elevated temperatures without affecting the yield (Table 1, entries 2 and 3). Unlike 2-thiophenecarboxaldehyde, a comparatively higher loading of 5 mol% of the catalyst had to be adopted at 80 °C in the case of 2-furfuraldehyde giving rise to a yield of 79% of

the ester in 1.5 h (Table 1, entries 8 and 9). An intramolecular Claisen–Tishchenko reaction was observed when *o*-phthalaldehyde was used, which with 5 mol% of the catalyst at 80 °C gave a yield of 77% of the phthalide cyclic ester in 1.5 h (Table 1, entry 10).

Furthermore, we tested alkali metal bis(trimethylsilyl)amides for this Claisen–Tishchenko reaction and found them to be efficient (Table 2). Much to our surprise, these readily available, simple alkali amides also catalyzed these reactions, but were as yet not documented in literature although alkaline earth amides[3j,k] and lanthanide amides[5b] as catalysts for such reactions were reported recently. Heavier amides are usually prepared from the alkali metal amides.[10] The activities of the alkali amides for the Claisen–Tishchenko reactions were found to increase from the almost inefficient Li[N(SiMe$_3$)$_2$] to the quite efficient K[N(SiMe$_3$)$_2$]. Although the reaction of benzaldehyde with 5 mol% of catalyst loading gave the ester at room temperature, a lower loading of 2.5 mol% was sufficient to give even better yield of the ester at 60 °C (Table 2, entries 3–6).

The *t*-BuOK-catalyzed disproportionation of benzaldehyde showed the formation of *tert*-butyl benzoate and benzyl alcohol, the latter is expected to be formed when potassium benzyloxide is quenched with water. A kinetic study of this reaction with benzaldehyde showed a linear relationship between 1/[reactant] and time indicating a second-order reaction with respect to the reactant, benzaldehyde (Figure 1). The metal alkoxide is assumed to be the active species, for which further evidence could be obtained from the ability of KH to catalyze this reaction with the same order, but appeared in comparison to be a little faster which is attributed to the direct formation of the potassium alkoxide (Table 2, entry 7). Based on these

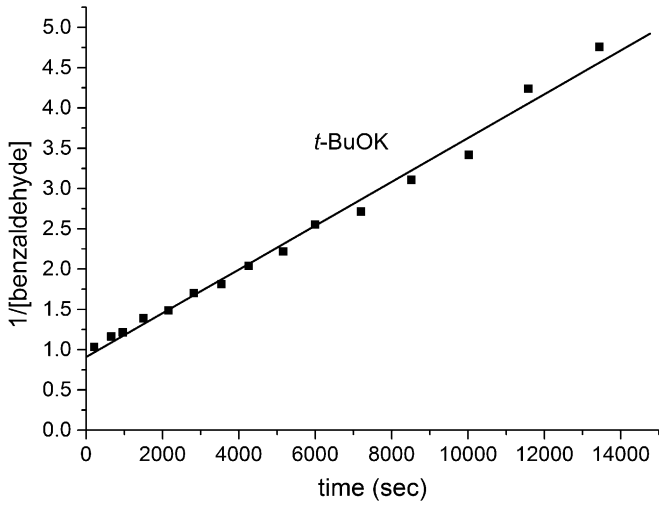
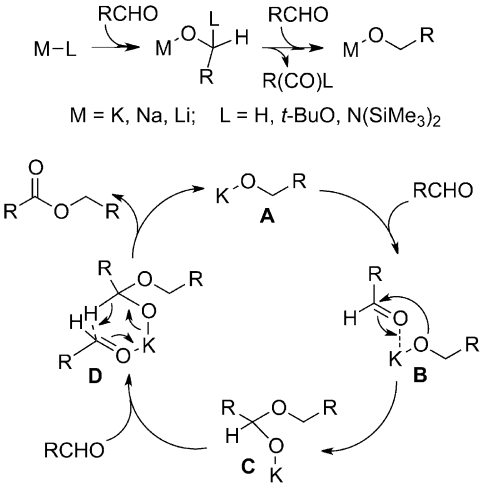


Figure 1. Linear plot of 1/[benzaldehyde] *vs.* time in the *t*-BuOK-catalyzed Claisen–Tishchenko reaction indicating a second order kinetics.



Scheme 2. Proposed mechanism for the Claisen–Tishchenko reaction catalyzed by KH/*t*-BuOK/K[N(SiMe$_3$)$_2$] with or without 18-crown-6 ether as a co-catalyst.

facts, a mechanism similar to one proposed for the lanthanide amide catalyses is suggested (Scheme 2).[5b] It worth mentioning that the KH-catalyzed disproportionation of benzaldehyde could be carried out even without any solvent giving rise to 97% yield of benzyl benzoate (Table 2, entry 8). When compared to *t*-BuOK as a catalyst and since the butyl ester cannot be formed, a higher amount of the catalyst appears to be present causing more of the product in the KH-catalyzed reaction (*cf.* Table 1, entries 6 and 9, respectively, to Table 2, entries 9 and 12). Using 5 mol% of KH, the aliphatic tertiary aldehyde, trimethyl acetaldehyde could be disproportionated to the corresponding ester in 93% yield (Table 2, entry 13).

However, in the case of *t*-BuONa similar observations were made as in the case of *t*-BuOK except that the reaction revealed a first order kinetic (Figure 2). Since *tert*-butyl benzoate is initially formed quantitatively with respect to the precatalyst *t*-BuONa, the formation of the sodium benzyloxide could not be the rate-determining step. So, it is assumed that either the insertion of aldehyde into the sodium alkoxide (**B**, Na instead of K) or the non- concerted hydride transfer from the formed sodium hemiacetal species (**C**, Na instead of K) to another molecule of aldehyde would be the rate-determining step. If the hydride transfer occurs in a concerted manner (**D**, Na instead of K), then the former would be the rate-determining step. However, the latter pathway, which would involve a β-hydride elimination from the sodium hemiacetal species to form NaH, seems not to be plausible.

Roesky and co-workers have rationalized a mechanism involving a concerted hydride transfer for homoleptic lanthanide amide-catalyzed Claisen–Tishchenko reaction,[5b] like the one suggested here for *t*-BuOK. A similar mechanism can be proposed for the

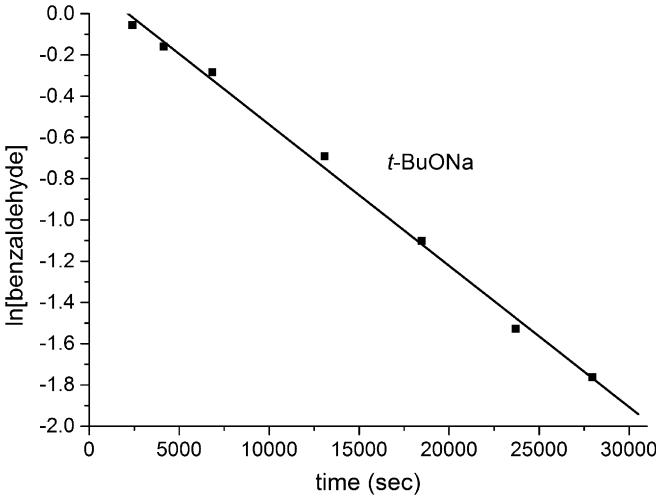
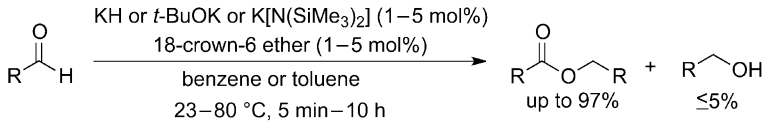


Figure 2. Linear plot of ln[benzaldehyde] *vs.* time in the *t*-BuONa-catalyzed Claisen–Tishchenko reaction indicating a first order kinetics.

$K[N(SiMe_3)_2]$-catalyzed disproportionation. At 30 min of the reaction of benzaldehyde with 0.5 equiv. of $K[N(SiMe_3)_2]$, GC/MS analysis showed benzyl benzoate, benzyl alcohol – which is expected to be formed when potassium benzyloxide is quenched with water, the hydrosilylated product benzyl trimethylsilyl ether and traces of other unidentified products. However, the major oxidized species could not be detected. Some of the above observations were also reported by Hill and co-workers in the case of alkaline earth metal amides catalyzing the Claisen–Tishchenko reaction.[3j]

In order to improve the rate of this disproportionation reaction catalyzed by potassium compounds, we added 18-crown-6 (1 equiv. with respect to the catalyst) (Table 3). The reaction rates were drastically improved in a few cases. With 1 mol% of *t*-BuOK and 18-crown-6 ether, the disproportionation of benzaldehyde in benzene was completed in 10 min at room temperature giving rise to 96% yield of benzyl benzoate with a TOF of 582 h^{-1} (Table 3, entry 1). Under the same reaction conditions and with the same loadings, KH showed a TOF of 1176 h^{-1} completing the reaction in 5 min with 97% yield of benzyl benzoate (Table 3, entry 2). With loadings of 2 mol% $K[N(SiMe_3)_2]$ and 18-crown-6 ether, the reaction showed a TOF of 6 h^{-1} giving rise to 91% yield of benzyl benzoate in 8 h. This strategy was adopted for the disproportionation of a few more aromatic aldehydes (Table 3, entries 3–7). However, when compared, addition of this crown ether decreased the efficiency in the case of 2-furfuraldehyde and 2-thienylcarboxaldehyde and was almost inactive for the disproportionation of 4-fluorobenzaldehyde. Since the active species involved is expected to be the 18-crown-6 ether potassium benzyloxide when any of these potassium compounds are used, we studied the kinetics of this reaction with benzaldehyde using the $K[N(SiMe_3)_2]$/18-crown-6 ether system and found it to be second order with respect to benzaldehyde, like

Table 3. Claisen–Tishchenko reaction catalyzed by potassium compounds along with 1 equiv. of 18-crown-6 ether with respect to the catalysts.



Entry	Product Ester [R]	Cat./[mol%]	TOF[a] [h^{-1}]	Time [h]	Yield[b] [%]
1		*t*-BuOK/1	582	0.17	96
2	phenyl	KH/1	1176	0.083	97
3		$K[N(SiMe_3)_2]$/2	6	8	91
4	4-chlorophenyl	KH/2	32	1.5	92
5	2-chlorophenyl	KH/2	144	0.33	95
6	4-bromophenyl	KH/1	291	0.33	95[c]
7	4-methoxyphenyl	KH/1	39	2.5	97
8	*tert*-butyl	KH/5	74	0.25	93[d]
9	cyclohexyl	KH/5	–	10	45[c,e]
10	*n*-pentyl	KH/3	–	3	–[f]

[a] TOF by GC/MS based on the consumption of the aldehyde.
[b] Unless mentioned, solvent: benzene; temperature 23 °C; isolated yield.
[c] Solvent: toluene
[d] Yield by ^1H NMR spectroscopy using mesitylene as internal standard.
[e] Temperature 80 °C.
[f] Aldol condensation products in 90% ($E/Z = 97/3$); traces of other isomers were also formed; yield by GC/MS based on the consumption of aldehyde.

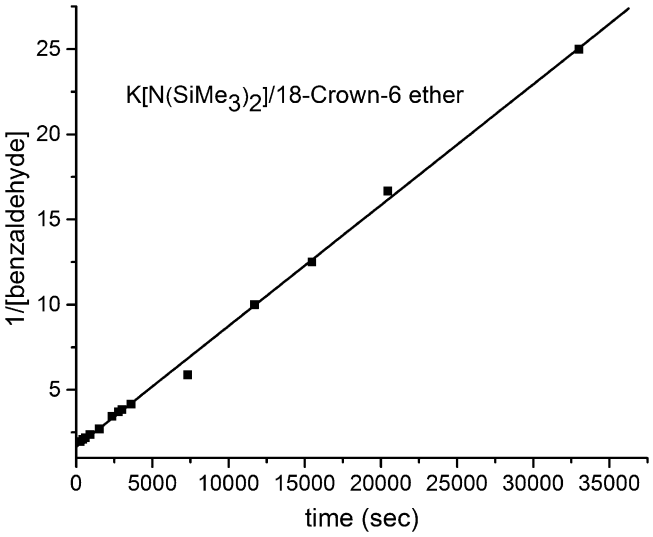


Figure 3. Linear plot of 1/[benzaldehyde] *vs.* time in the $K[N(SiMe_3)_2]$/18-crown-6 ether-catalyzed Claisen–Tishchenko reaction indicating a second order kinetics.

the one without 18-crown-6 ether, indicating a similar mechanism (Figure 3). We suppose that the increased activity by adding the crown ether is caused by an increased solubility of the potassium (crown ether) salt.

Then, we tested this strategy also for aliphatic primary, secondary and tertiary aldehydes as reaction substrates. The aliphatic tertiary aldehyde, trimethylacetaldehyde could be disproportionated to the corresponding ester in 93% yield within 15 min at room temperature using KH and 18-crown-6 ether loadings of 5 mol% (Table 3, entry 8). Though the reaction was not uniform, addition of 5 mol% of KH and 18-crown-6 ether at a temperature of 80 °C was adopted for the disproportionation of the aliphatic aldehyde, cyclohexanecarboxaldehyde, which gave 45% yield of the desired ester in 10 h (Table 3, entry 9). However, aldehydes possessing a methylene group at the α-position to the aldehyde functionality, hexanal for instance, revealed under the conditions of the addition of 3 mol% of KH and 18-crown-6 ether at room temperature, formation of aldol condensation products in >90% yield ($E/Z = 97/3$) (Table 3, entry 10).

In summary, the simple, cheap, shelf-available *t*-BuOK and KH, as well as *t*-BuONa are efficient catalysts for the Claisen–Tishchenko disproportionation of aromatic and even heteroaromatic aldehydes, as well as of aliphatic secondary and tertiary aldehydes. Alternatively, aldol condensation products were formed when primary aldehydes were used. Addition of a catalytic quantity of 18-crown-6 ether could increase the rate of reaction in some cases. The simple potassium and sodium metal amides, although less efficient for the disproportionation reaction when compared to the corresponding homoleptic lanthanide amides, as well as alkaline earth amides, could provide the product with acceptable rates and yields. Higher efficiencies of the catalysts are expected to be achieved by utilizing the opportunity of ligand sphere tuning, particularly with transition metals as well as lanthanides and actinides, which has acquired sufficient interest in recent times and as mentioned, we are also involved in developing this transformation using suitable rhenium complexes. This would also impart help to overcome the limitations of any primary aliphatic aldehydes, as well as to effect cross-Claisen–Tishchenko disproportionation.

Experimental Section

Alkali Metal Compounds-Catalyzed Claisen–Tishchenko Reaction

t-BuOK (10 mg, 0.089 mmol) was charged in a 10-mL glass vial (for room temperature reactions) or a 25-mL Young Schlenk tube (for heating reactions). Toluene (1 mL) was added to it. To this, benzaldehyde (945.8 mg, 8.9 mmol) was added followed by another portion of toluene (1 mL). The vessel was closed and the mixture was stirred (in the glove box itself for room temperature reactions or kept outside in an oil bath for heating reactions). The reaction was monitored by GC/MS for which the samples were taken in the glove box, quenched immediately with water outside. When the reaction was completed, the mass was concentrated to dryness. It was purified by silica gel flash column chromatography (eluent: hexane/ethyl acetate) to afford benzyl benzoate as a pale yellow liquid; yield: 907.1 mg (4.274 mmol, 96%).

The KH, *t*-BuONa, $K[N(SiMe_3)_2]$ and $Na[N(SiMe_3)_2]$ catalyzed Claisen–Tishchenko reactions were also performed in a similar manner.

Potassium Compounds/18-Crown-6 Ether-Catalyzed Claisen–Tishchenko Reaction

KH (3 mg, 0.0748 mmol) and 18-crown-6 ether (19.75 mg, 0.0748 mmol) were charged in a Young NMR tube. Benzene-d_6 (0.3 mL) was added to it. To this, benzaldehyde (793.7 mg, 7.48 mmol) was added followed by another portion of benzene-d_6 (0.3 mL). The tube was closed and the reaction mass was shaken well. The reaction was monitored by ^{1}H NMR spectroscopy for the absence of benzaldehyde. When the reaction was completed, the mass was concentrated to dryness. It was purified by silica gel flash column chromatography (eluent: hexane/ethyl acetate) to afford benzyl benzoate as a pale yellow liquid; yield: 767.35 mg (3.615 mmol, 97%).

t-BuOK/18-crown-6 ether and $K[N(SiMe_3)_2]$/18-crown-6 ether catalyzed Claisen–Tishchenko reactions were also performed in a similar manner.

Acknowledgements

Funding from the Swiss National Science Foundation and the University of Zurich is gratefully acknowledged.

References

[1] a) L. Claisen, *Ber. Dtsch. Chem. Ges.* **1887**, *20*, 646–650; b) W. Tischtschenko, *Chem. Zentralbl.* **1906**, *77*, I, 1309–1311; c) T. Seki, T. Nakajo, M. Onaka, *Chem. Lett.* **2006**, *35*, 824–829; d) M. H. S. A. Hamid, P. A. Slatford, J. M. J. Williams, *Adv. Synth. Catal.* **2007**, *349*, 1555–1575; e) K. Ekoue-Kovi, C. Wolf, *Chem. Eur. J.* **2008**, *14*, 6302–6315; f) W. I. Dzik, L. J. Gooßen, *Angew. Chem.* **2011**, *123*, 11241–11243; *Angew. Chem. Int. Ed.* **2011**, *50*, 11047–11049.

[2] a) *Ullmann's Encyclopadia of Industrial Chemistry*, 6th edn., Wiley-VCH, Weinheim, **2002**.

[3] a) O. Kamm,W. F. Kamm, *Org. Synth. Coll. Vol. 1*, **1941**,104; b) F. W. Swamer, C. R. Hauser, *J. Am. Chem. Soc.* **1946**, *68*, 2647–2649; c) W. C. Child, H. Atkins, *J. Am. Chem. Soc.***1923**, *45*, 3013–3023; d) Y. Ogata, A. Kawasaki, *Tetrahedron* **1969**, *25*, 929–935; e) T. Ooi, T. Miura, K. Takaya, *Tetrahedron Lett.* **1999**, *40*, 7695–7698; f) I. Simpura, V. Nevalainen, *Tetrahedron* **2001**, *57*, 9867–9872; g) T. Ooi, K. Ohmatsu, K. Sasaki, T. Miura, K. Maruoka, *Tetrahedron Lett.* **2003**, *44*, 3191–3193; h) P. R. Stupp, *J. Org. Chem.* **1973**, *38*, 1433–1434; i) Y.-S. Hon, Y.-C. Wong, C.-P. Chang, C.-H. Hsieh, *Tetrahedron* **2007**, *63*, 11325–11340; j) M. R. Crimmin, A. G. M. Barrett, M. S. Hill, P. A. Procopiou, *Org. Lett.* **2007**, *9*, 331–333; k) B. M. Day, N. E. Mansfield, M. P. Coles, P. B. Hitchcock, *Chem. Commun.* **2011**, *47*, 4995–4997; l) M. M. Mojtahedi, E. Akbarzadeh, R. Sharifi, M. S. Abaee, *Org. Lett.* **2007**, *9*, 2791–2793; m) D. C. Waddell, J. Mack, *Green Chem.* **2009**, *11*, 79–82; n) T. Werner, J. Koch, *Eur. J. Org. Chem.* **2010**, 6904–6907; o) L. Cronin, F. Manoni, C. J. O' Connor, S. J. Connon, *Angew. Chem.* **2010**, *122*, 3109–3112; *Angew. Chem. Int. Ed.* **2010**, *49*, 3045–3048; p) S. P Curran, S. J. Connon, *Org. Lett.* **2012**, *14*, 1074–1077.

[4] a) M. Yamashita, Y. Watanabe, T.-A. Mitsudo, Y. Takegami, *Bull. Chem. Soc. Jpn.* **1976**, *49*, 3597–3600; b) M. Yamashita, T. Ohishi, *Appl. Organomet. Chem.* **1993**, *7*, 357–361; c) H. Horino, T. Ito, A. Yamamoto, *Chem. Lett.* **1978**, *7*, 17–20; d) T. Ito, H. Horino, Y. Koshiro, A. Yamamoto, *Bull. Chem. Soc. Jpn.* **1982**, *55*, 504–512; e) N. Menashe, Y. Shvo, *Organometallics* **1991**, *10*, 3885–3891; f) V. V. Grushin, H. Alper, *J. Org. Chem.* **1991**, *56*, 5159–5161; g) A. Sorkau, K. Schwarzer, C. Wagner, E. Poetsch, D. Steinborn, *J. Mol. Catal. A* **2004**, *224*, 105–109; h) M.-O. Simon, S. Darses, *Adv. Synth. Catal.* **2010**, *352*, 305–308; i) M. Massoui, D. Beaupére, L. Nadjo, R. Uzan, *J. Organomet. Chem.* **1983**, *259*, 345–348; j) C. Tejel, M. A. Ciriano V. Passarelli, *Chem. Eur. J.* **2011**, *17*, 91–95; k) S. H. Bergens, D. P. Fairlie, B. Bosnich, *Organometallics* **1990**, *9*, 566–571; l) P. Barrio, M. A. Esteruelas, E. Onate, *Organometallics* **2004**, *23*, 1340–1348; m) T. Suzuki, T; Yamada, T. Matsuo, K. Watanabe, T. Katoh, *Synlett* **2005**, 1450–1452; n) T. Suzuki, T. Yamada, K. Watanabe, T. Katoh, *Bioorg. Med. Chem. Lett.* **2005**, *15*, 2583–2585; o) S. Ogoshi, Y. Hoshimoto, M. Ohashi, *Chem. Commun.* **2010**, *46*, 3354–3356; p) Y. Hoshimoto, M. Ohashi, S. Ogoshi, *J. Am. Chem. Soc.* **2011**, *133*, 4668–4671; q) K.-I. Morita, Y. Nishiyama, Y. Ishii, *Organometallics* **1993**, *12*, 3748–3752.

[5] a) S. Onozawa, T. Sakakura, M. Tanaka, M. Shiro, *Tetrahedron* **1996**, *52*, 4291–4302; b) H. Berberich, P. W. Roesky, *Angew. Chem.* **1998**, *110*, 1618–1620; *Angew. Chem. Int. Ed.* **1998**, *37*, 1569–1571; c) G. B. Deacon, A. Gitlits, P. W. Roesky, M. R. Bürgstein, K. C. Lim, B. W. Skelton, A. H. White, *Chem. Eur. J.* **2001**, *7*, 127–138; d) M. R. Burgstein, H. Berberich, P. W. Roesky, *Chem. Eur. J.* **2001**, *7*, 3078–3085; e) A. Zuyls, P. W. Roesky, G. B. Deacon, K. Konstas, P. C. Junk, *Eur. J. Org. Chem.* **2008**, 693–697; f) J.-L. Hsu, J.-M. Fang, *J. Org. Chem.* **2001**, *66*, 8573–8584; g) A. Michrowska, B. List, *Nature Chem.* **2009**, *1*, 225–228; h) T. Andrea, E. Barnea, M. S. Eisen, *J. Am. Chem. Soc.* **2008**, *130*, 2454–2455; i) M. Sharma, T. Andrea, N. J. Brookes, B. F. Yates, M. S. Eisen, *J. Am. Chem. Soc.* **2011**, *133*, 1341–1356.

[6] A. Chan, K. A. Scheidt, *J. Am. Chem. Soc.* **2006**, *128*, 4558–4559.

[7] T. Seki, K. Akutsu, H. Hattori, *Chem. Commun.* **2001**, 1000–1001.

[8] a) B. Dudle, K. Rajesh, O. Blacque, H. Berke, *J. Am. Chem. Soc.* **2011**, *133*, 8168–8178.

[9] K. Rajesh, B. Dudle, O. Blacque, H. Berke, *Adv. Synth. Catal.* **2011**, *353*, 1479–1484.

[10] a) D. C. Bradley, J. S. Ghorta, F. A. Hart, *J. Chem. Soc. Dalton Trans.* **1973**, 1021–1023; b) M. H. Chisholm, J. Gallucci, K. Phomphari, *Chem. Commun.* **2003**, 48–49; c) M. H. Chisholm, J. Gallucci, K. Phomphrai, *Inorg. Chem.* **2004**, *43*, 6717–6725.

Supporting Information

Alkali Metal *tert*-Butoxides, Hydrides and Bis(trimethylsilyl)amides as Efficient Homogeneous Catalysts for Claisen-Tishchenko Reaction†

Kunjanpillai Rajesh and Heinz Berke*

Institute of Inorganic Chemistry University of Zürich, Winterthurerstrasse 190, CH-8057, Zürich, Switzerland; Fax: 41-1-635-6802; E-mail: hberke@aci.uzh.ch

General Information

All manipulations were carried out under an atmosphere of dry nitrogen using standard Schlenk techniques or in a glove box (M. Braun 150B-G-II) filled with dry nitrogen. Solvents were freshly distilled under N_2 by employing standard procedures. NaH, *t*-BuONa, *t*-BuOK, *t*-BuOK (sublimed grade, 99.99% trace metals basis), NaN[$(SiMe_3)_2$] and K[$N(SiMe_3)_2$] were purchased from Aldrich. KH in mineral oil was purchased from Acros Organics. Both NaH and KH were washed with hexane in a glove box and the dry powders were stored in the glove box. Redistilled benzaldehyde purchased from Aldrich chemical company and all other aldehydes purchased either from Aldrich or ABCR chemical companies were used as such. NMR analyses were carried out on a Varian Gemini 300 spectrometer. GC/MS analyses were carried out on a Varian Saturn 2000 GC/MS spectrometer.

Kinetic Studies

Kinetics of the *t*-BuOK and *t*-BuONa reactions were carried out in toluene in a Young Schlenk where as the K[$N(SiMe_3)_2$]/18-crown-6 ether catalyzed reaction was carried out in benzene in a Young NMR tube.

Purification of Products

All the products were obtained by purification using silica gel column chromatography (Eluent: Hexane/Ethyl acetate) except cyclohexylmethyl cyclohexanecarboxylate which was isolated by distillation.

Characterization Data

Benzyl benzoate

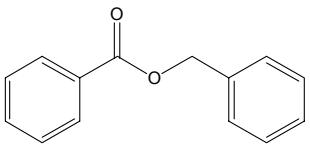


Table 1, entry 1: Using 1 mol% of *t*-BuOK (10 mg, 0.089 mmol) in toluene (2 mL) at rt, the aldehyde (945.8 mg, 8.9 mmol) was dimerized to yield 96% of the ester (908 mg, 4.278 mmol).

Table 2, entry 7: Using 1 mol% of KH (5 mg, 0.125 mmol) in toluene at rt (2.5 mL), the aldehyde (1.323 g, 12.5 mmol) was dimerized to yield 97% of the ester (1.283 g, 6.045 mmol).

Table 2, entry 8: Using 1 mol% of KH (5 mg, 0.125 mmol) in neat conditions at rt (2.5 mL), the aldehyde (1.323 g, 12.5 mmol) was dimerized to yield 97% of the ester (1.283 g, 6.045 mmol).

Table 2, entry 1: Using 5 mol% of *t*-BuONa (10 mg, 0.104 mmol) in toluene (0.8 mL) at rt, the aldehyde (220.9 mg, 2.08 mmol) was dimerized to yield 86% of the ester (189.9 mg, 0.895 mmol).

Table 2, entry 3: Using 5 mol% of $Na[N(SiMe_3)_2]$ (10 mg, 0.0545 mmol) in toluene (0.6 mL) at rt, the aldehyde (115.7 mg, 1.09 mmol) was dimerized to yield 85% of the ester (98.35 mg, 0.463 mmol).

Table 2, entry 4: Using 5 mol% of $K[N(SiMe_3)_2]$ (10 mg, 0.05 mmol) in toluene (0.6 mL) at rt, the aldehyde (106.4 mg, 1.0 mmol) was dimerized to yield 86% of the ester (91.50 mg, 0.431 mmol).

Table 2, entry 5: Using 2.5 mol% of $Na[N(SiMe_3)_2]$ (10 mg, 0.0545 mmol) in toluene (1 mL) at 60 °C, the aldehyde (231.5 mg, 2.18 mmol) was dimerized to yield 88% of the ester (203.7 mg, 0.961 mmol).

Table 2, entry 6: Using 2.5 mol% of $K[N(SiMe_3)_2]$ (10 mg, 0.05 mmol) in toluene (1 mL) and at 60 °C, the aldehyde (212.79 mg, 2.0 mmol) was dimerized to yield 90% of the ester (191.5 mg, 0.902 mmol).

Table 3, entry 1: Using 1 mol% each of *t*-BuOK (5 mg, 0.0446 mmol) and 18-crown-6 ether (11.77 mg, 0.0446 mmol) in benzene (0.4 mL) at rt, the aldehyde (472.9 mg, 4.456 mmol) was dimerized to yield 96% of the ester (457.8 mg, 2.157 mmol).

Table 3, entry 2: Using 1 mol% each of KH (3 mg, 0.0748 mmol) and 18-crown-6 ether (19.75 mg, 0.0748 mmol) in benzene (0.6 mL) at rt, the aldehyde (793.7 mg, 7.48 mmol) was dimerized to yield 97% of the ester (769.89 mg, 3.627 mmol).

Table 3, entry 3: Using 1 mol% each of $K[N(SiMe_3)_2]$ (10 mg, 0.05 mmol) and 18-crown-6 ether (13.24 mg, 0.05 mmol) in benzene (0.4 mL) at rt, the aldehyde (266.0 mg, 2.51 mmol) was dimerized to yield 91% of the ester (242.05 mg, 1.14 mmol).

^{1}H NMR (300 MHz, $CDCl_3$): δ 5.41 (s, 2H), 7.38-7.51 (m, 7H), 7.57-7.62 (m, 1H), 8.11-8.14 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 66.6, 128.1, 128.2, 128.3, 128.5, 129.6, 130.1, 133.0, 136.0, 166.3.

4-Methoxybenzyl 4-methoxybenzoate

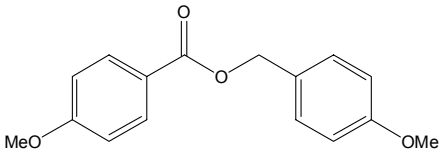


Table 1, entry 7: Using 2 mol% of *t*-BuOK (10 mg, 0.089 mmol) in toluene (2 mL) at rt, the aldehyde (606.5 mg, 4.455 mmol) was dimerized to yield 92% of the ester (558.0 mg, 2.049 mmol).

Table 3, entry 7: Using 1 mol% each of KH (3 mg, 0.0748 mmol) and 18-crown-6 ether (19.75 mg, 0.0748 mmol) in benzene (0.6 mL) at rt, the aldehyde (1.018 g, 7.48 mmol) was dimerized to yield 97% of the ester (987.8 mg, 3.627 mmol).

^{1}H NMR (300 MHz, $CDCl_3$): δ 3.82 (s, 3H), 3.85 (s, 3H), 5.29 (s, 2H), 6.90-6.94 (m, 4H), 7.38-7.41 (m, 2H), 8.02-8.05 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 55.3, 55.4, 66.2, 113.6, 113.9, 122.7, 128.4, 130.0, 131.7, 159.6, 163.4, 166.2.

4-Fluorobenzyl 4-fluorobenzoate

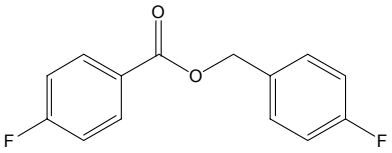


Table 1, entry 6: Using 5 mol% of *t*-BuOK (10 mg, 0.089 mmol) in toluene (0.6 mL) at 80 °C, the aldehyde (221.2 mg, 1.782 mmol) was dimerized to yield 80% of the ester (177.0 mg, 0.713 mmol).

Table 2, entry 9: Using 5 mol% of KH (5 mg, 0.125 mmol) in toluene at 80 °C (0.6 mL), the aldehyde (0.309 g, 2.493 mmol) was dimerized to yield 84% of the ester (259.6 g, 1.046 mmol).

^{1}H NMR (300 MHz, $CDCl_3$): δ 5.33 (s, 2H), 7.06-7.15 (m, 4H), 7.41-7.46 (m, 2H), 8.06-8.11 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 66.2, 115.6 (d, J = 21.7 Hz), 126.4 (d, J = 3.1 Hz), 130.3 (d, J = 8.2 Hz), 131.9 (d, J = 3.1 Hz), 132.3 (d, J = 9.3 Hz), 161.1, 164.3 (d, J = 14.3 Hz), 165.4, 167.6.

4-Chlorobenzyl 4-chlorobenzoate

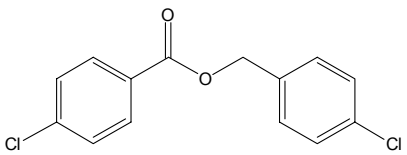


Table 1, entry 2: Using 2 mol% of *t*-BuOK (10 mg, 0.089 mmol) in toluene (2 mL) at rt, the aldehyde (626.6 mg, 4.456 mmol) was dimerized to yield 94% of the ester (589.0 mg, 2.095 mmol).

Table 2, entry 10: Using 5 mol% of $K[N(SiMe_3)_2]$ (10 mg, 0.05 mmol) in toluene (0.8 mL) at 60 °C, the aldehyde (140.94 mg, 1.003 mmol) was dimerized to yield 86% of the ester (121.2 mg, 0.431 mmol)

Table 3, entry 4: Using 2 mol% each of KH (3 mg, 0.0748 mmol) and 18-crown-6 ether (19.75 mg, 0.0748 mmol) in benzene (0.6 mL) at rt, the aldehyde (525.7 mg, 3.74 mmol) was dimerized to yield 92% of the ester (483.64 mg, 1.72 mmol).

^{1}H NMR (300 MHz, $CDCl_3$): δ 5.33 (s, 2H), 7.38-7.46 (m, 6H), 7.40-7.45 (m, 2H), 7.99-8.02 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 66.1, 128.3, 128.8, 128.8, 129.6, 131.1, 134.3, 134.3, 139.6, 165.4

4-Bromobenzyl 4-bromobenzoate

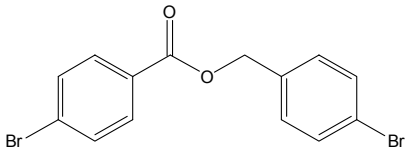


Table 1, entry 5: Using 2 mol% of *t*-BuOK (10 mg, 0.089 mmol) in toluene (2 mL) at rt, the aldehyde (824.4 mg, 4.456 mmol) was dimerized to yield 93% of the ester (766.7 mg, 2.072 mmol).

Table 2, entry 11: Using 3 mol% of $K[N(SiMe_3)_2]$ (10 mg, 0.05 mmol) in toluene (0.8 mL) and at 60 °C, the aldehyde (309.1 mg, 1.671 mmol) was dimerized to yield 85% of the ester (262.74 mg, 0.710 mmol)

Table 3, entry 6: Using 1 mol% each of KH (3 mg, 0.0748 mmol) and 18-crown-6 ether (19.75 mg, 0.0748 mmol) in toluene (2 mL) at rt, the aldehyde (1.384 g, 7.48 mmol) was dimerized to yield 95% of the ester (1.315 mg, 3.55 mmol).

^{1}H NMR (300 MHz, $CDCl_3$): δ 5.31 (s, 2H), 7.27-7.34 (m, 2H), 7.52-7.61 (m, 4H), 7.91-7.94 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 66.2, 122.4, 128.3, 128.8, 129.9, 131.2, 131.8, 131.8, 134.7, 165.5.

2-Chlorobenzyl 2-chlorobenzoate

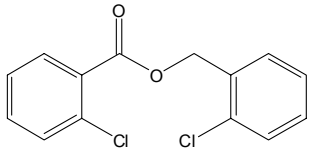


Table 1, entry 4: Using 2 mol% of *t*-BuOK (10 mg, 0.089 mmol) in toluene (2 mL) at rt, the aldehyde (626.6 mg, 4.456 mmol) was dimerized to yield 92% of the ester (576.5 mg, 2.05 mmol).

Table 3, entry 5: Using 2 mol% each of KH (3 mg, 0.0748 mmol) and 18-crown-6 ether (19.75 mg, 0.0748 mmol) in benzene (0.6 mL) at rt, the aldehyde (525.7 mg, 3.74 mmol) was dimerized to yield 95% of the ester (499.42 mg, 1.776 mmol).

^{1}H NMR (300 MHz, $CDCl_3$): δ 5.49 (s, 2H), 7.27-7.34 (m, 3H), 7.39-7.48 (m, 3H), 7.53-7.57 (m, 1H), 7.88-7.91 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 64.6, 126.6, 126.9, 129.7, 129.7, 130.1, 131.1, 131.6, 132.7, 133.2, 133.8, 133.9, 165.1.

Isobenzofuran-1(3*H*)-one

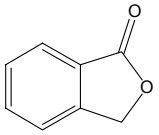


Table 1, entry 10: Using 5 mol% of *t*-BuOK (10 mg, 0.089 mmol) in toluene (2 mL) at 80 °C, the aldehyde (239.07 mg, 1.782 mmol) was dimerized to yield 77% of the ester (184.08 mg, 1.372 mmol).

^{1}H NMR (300 MHz, $CDCl_3$): δ 5.31 (s, 2H), 7.49-7.54 (m, 2H), 7.66-7.71 (m, 1H), 7.86-7.89 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 69.9, 122.3, 125.4, 125.6, 129.1, 134.1, 146.7, 171.2.

Furan-2-ylmethyl furan-2-carboxylate

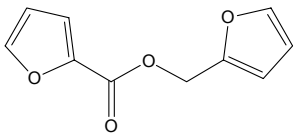


Table 1, entry 9: Using 5 mol% of *t*-BuOK (10 mg, 0.089 mmol) in toluene (2 mL) at 80 °C, the aldehyde (171.25 mg, 1.782 mmol) was dimerized to yield 79% of the ester (135.29 mg, 0.704 mmol).

Table 2, entry 12: Using 5 mol% of KH (5 mg, 0.125 mmol) in toluene at 80 °C (0.6 mL), the aldehyde (239.54 mg, 2.493 mmol) was dimerized to yield 83% of the ester (198.82 g, 1.035 mmol).

^{1}H NMR (300 MHz, $CDCl_3$): δ 5.29 (s, 2H), 6.36-6.38 (m, 1H), 6.48-6.50 (m, 2H), 7.19-7.20 (m, 1H), 7.43-7.44 (m, 1H), 7.56-7.57 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 58.2, 110.6, 111.2, 111.8, 118.4, 143.4, 144.2, 146.5, 149.0, 158.2.

Thiophen-2-ylmethyl thiophene-2-carboxylate

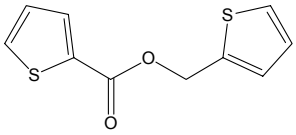


Table 1, entry 8: Using 2 mol% of *t*-BuOK (10 mg, 0.089 mmol) in toluene (2 mL) at rt, the aldehyde (499.7 mg, 4.456 mmol) was dimerized to yield 88% of the ester (439.76 mg, 1.961 mmol).

^{1}H-NMR (300 MHz, $CDCl_3$): δ 5.50 (s, 2H), 7.01 (dd, *J* = 3.6, 5.1 Hz, 1H), 7.09 (dd, *J* = 3.9, 5.1 Hz, 1H), 7.18 (dd, *J* = 0.6, 3.3 Hz, 1H), 7.35 (dd, *J* = 1.2, 5.1 Hz, 1H), 7.56, (dd, *J* = 1.2, 4.8 Hz, 1H), 7.83 (dd, *J* = 1.2, 3.9 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 61.1, 126.8, 127.0, 127.8, 128.4, 132.7, 133.4, 133.8, 137.8, 161.9.

Cyclohexylmethyl cyclohexanecarboxylate

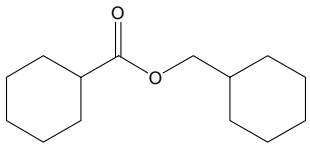
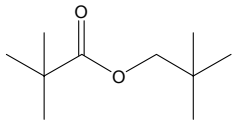


Table 3, entry 9: Using 5 mol% each of KH (5 mg, 0.125 mmol) and 18-crown-6 ether (32.92 mg, 0.125 mmol) in toluene (0.6 mL) at rt, the aldehyde (279.66 mg, 2.49 mmol) was dimerized to yield 45% of the ester by distillation (125.85 mg, 0.561 mmol).

^{1}H NMR ($CDCl_3$, 400 MHz) 0.90-1.02 (m, 2H), 1.19-1.49 (m, 8H), 1.61-1.73 (m, 9H), 1.87-1.92 (m, 2H), 2.29 (tt, *J* = 3.3, 11.1 Hz, 9H), 3.86 (d, J = 6.3 Hz 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) 25.4, 25.7, 25.7, 26.3, 29.0, 29.6, 37.1, 43.2, 69.2, 176.1

2,2-dimethylpropyl 2,2-dimethylpropanoate



Due to its comparatively low boiling point, this compound was directly analyzed by ^{1}H NMR spectroscopy using mesitylene as internal standard.

Table 2, entry 13: Using 5 mol% of KH (5 mg, 0.125 mmol in benzene (0.6 mL) at rt, the aldehyde (214.75 mg, 2.49 mmol) was dimerized to yield 93% of the ester .

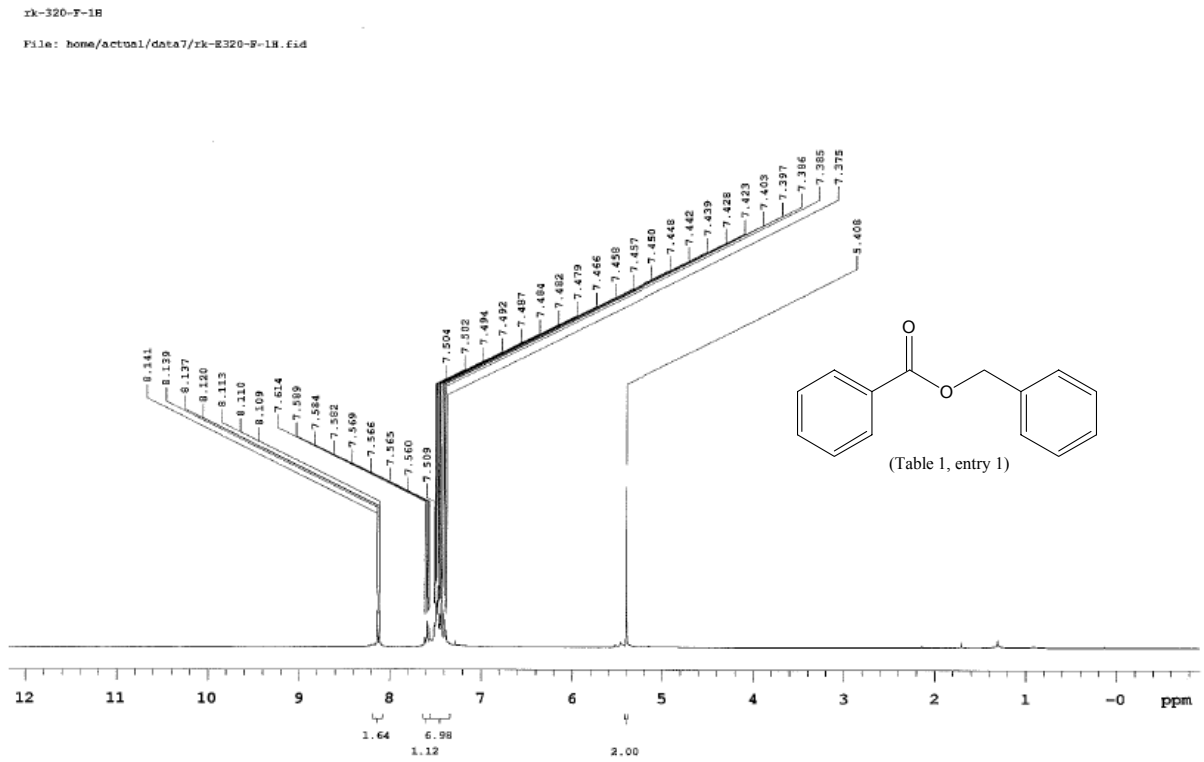
Table 3, entry 8: Using 5 mol% each of KH (5 mg, 0.125 mmol) and 18-crown-6 ether (32.92 mg, 0.125 mmol) in benzene (0.6 mL) at rt, the aldehyde (214.75 mg, 2.49 mmol) was dimerized to yield 93% of the ester

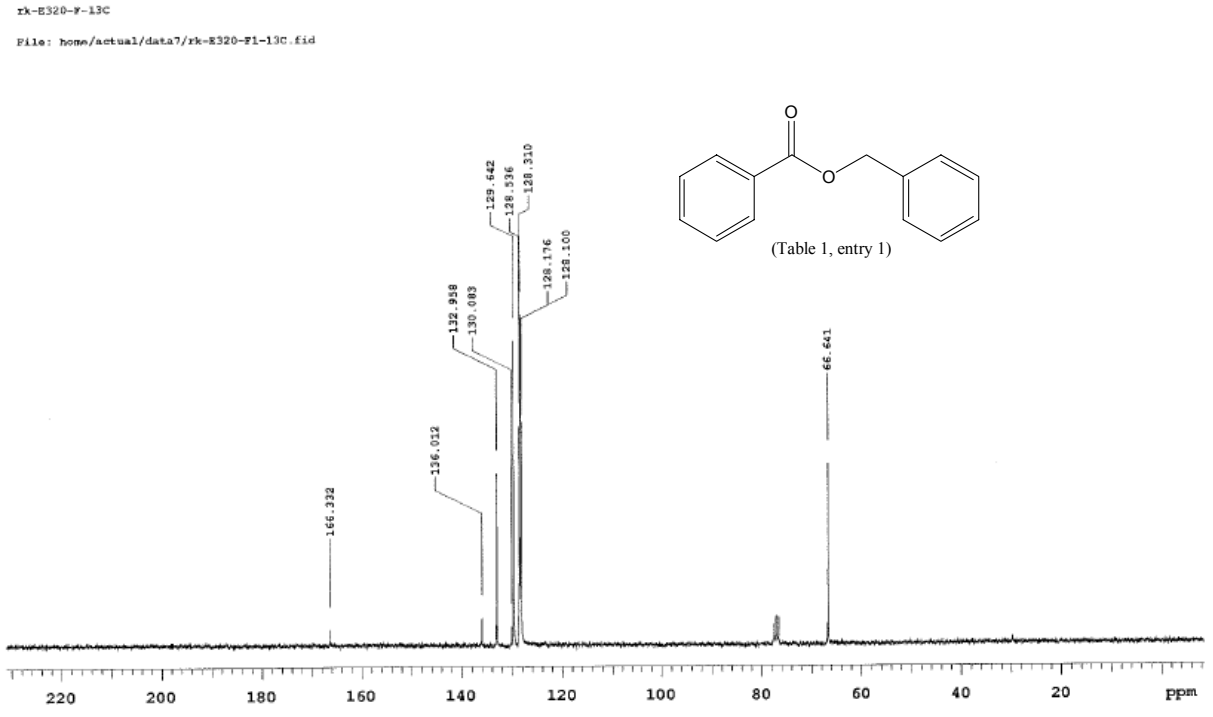
^{1}H NMR (300 MHz, $CDCl_3$, mesitylene): δ 0.83 (s, 9H), 1.18 (s, 9H), 3.71 (s, 2H).

References

1. T. Werner, J. Koch, *Eur. J. Org. Chem*. **2010**, 6904-6907.
2. M. R. Crimmin, A. G. M. Barrett, M. S. Hill, P. A. Procopiou, *Org. Lett*. **2007**, *9*, 331-333;

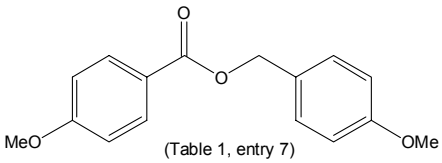
^{1}H and ^{13}C NMR Spectra



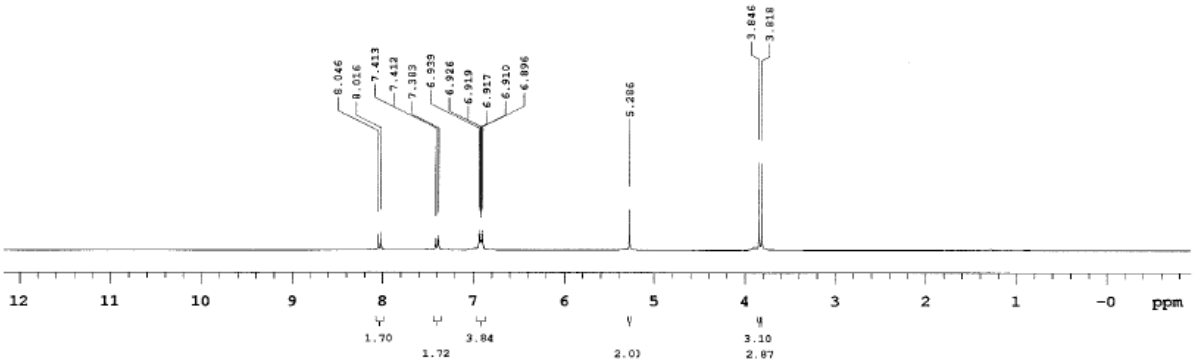


rk-E348-F-1H

File: xp

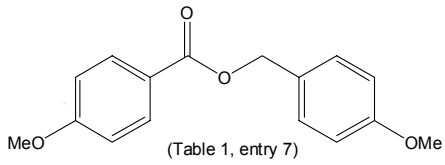


(Table 1, entry 7)

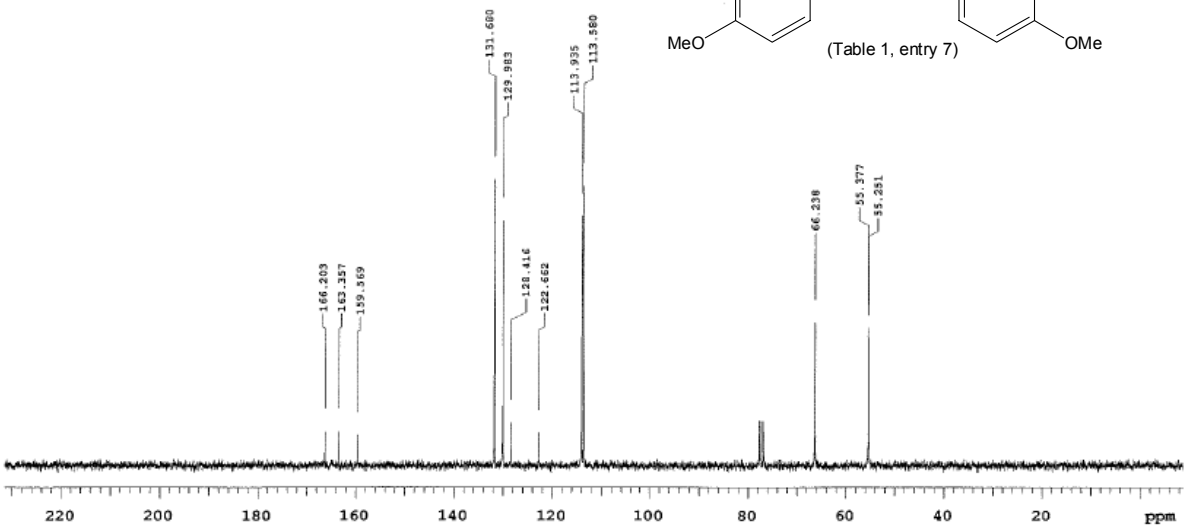


rk-F348-F-13C

File: home/actual/data7/rk-E348-F1-13C.fid

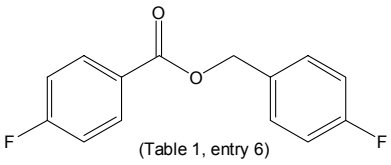


(Table 1, entry 7)

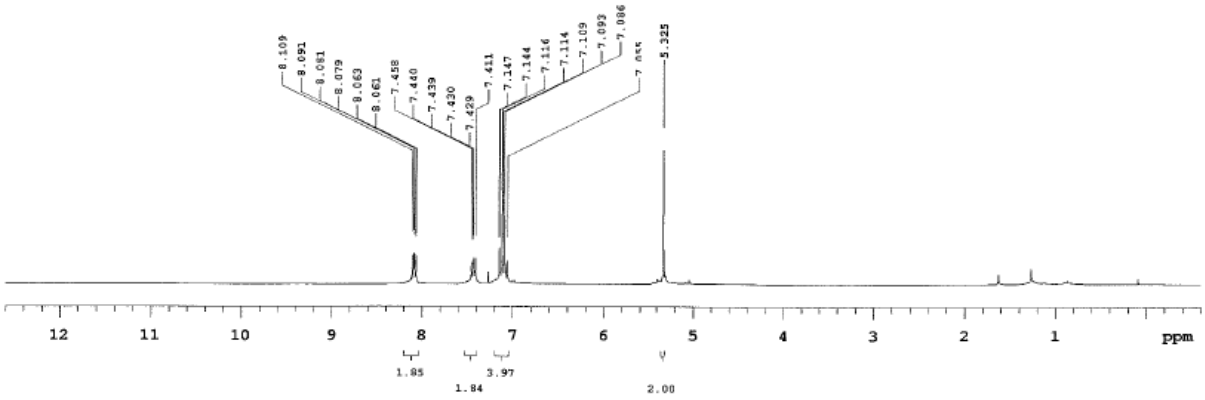


rk-F211-F-1H

File: home/actual/data7/rk-F211-F-1H.fid

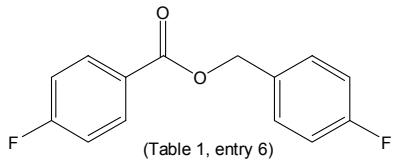


(Table 1, entry 6)



rk-F211-F-13C

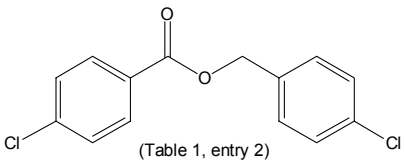
File: home/actual/data7/rk-F211-F2-13C.fid



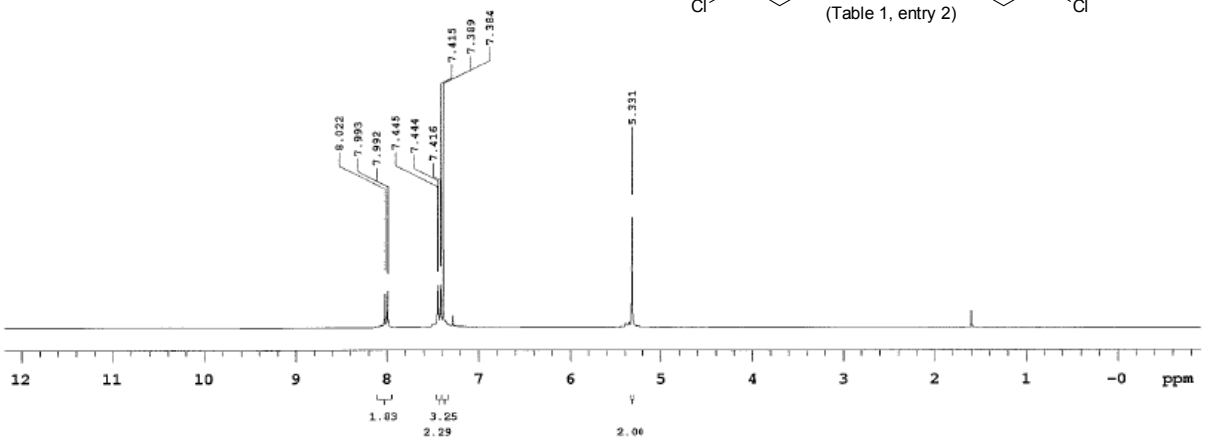
(Table 1, entry 6)

rk-E341-F-1H

File: home/actual/data7/rk-E341-F-1H.fid

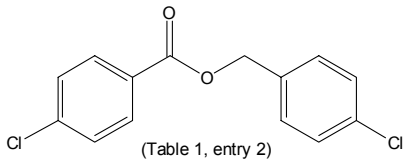


(Table 1, entry 2)



rk-F341-F-13C

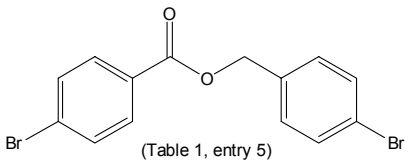
File: home/actual/data7/rk_E341-F-13C.fid



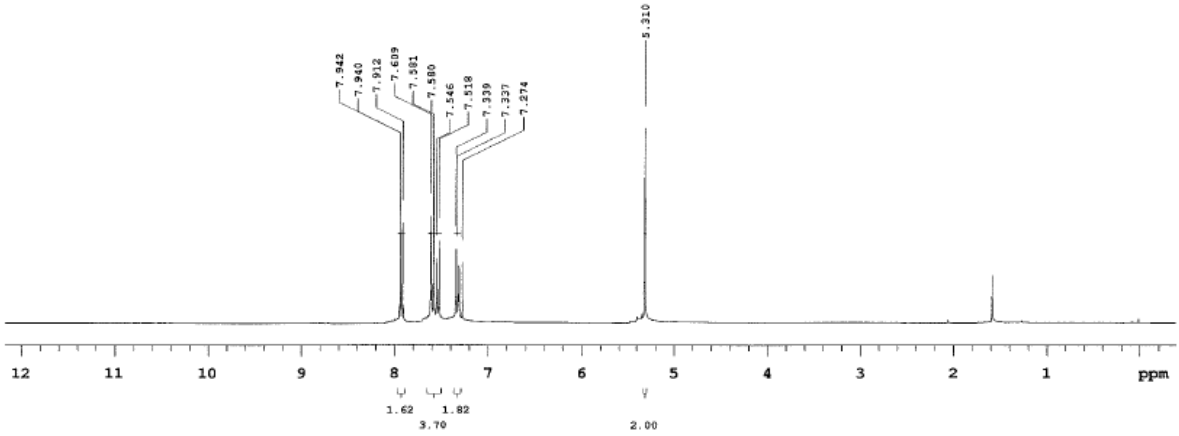
(Table 1, entry 2)

rk-F205-F-1H

File: home/actual/data7/rk-F205-F-1H.fid

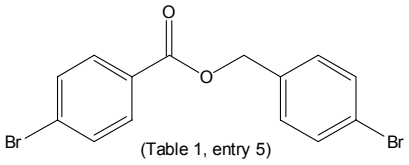


(Table 1, entry 5)

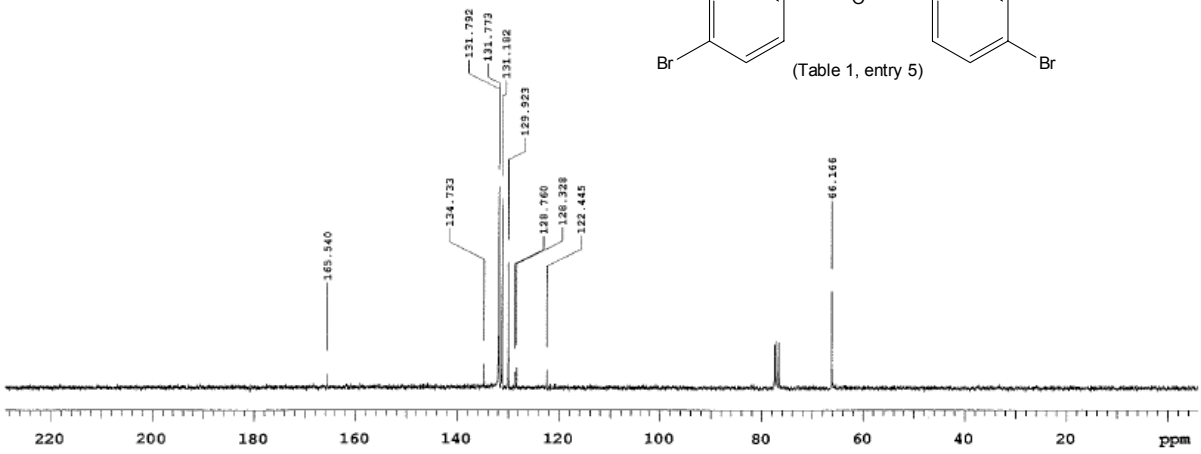


rk-F205-F-13C

File: home/actual/data7/rk-F205-F-13C.fid

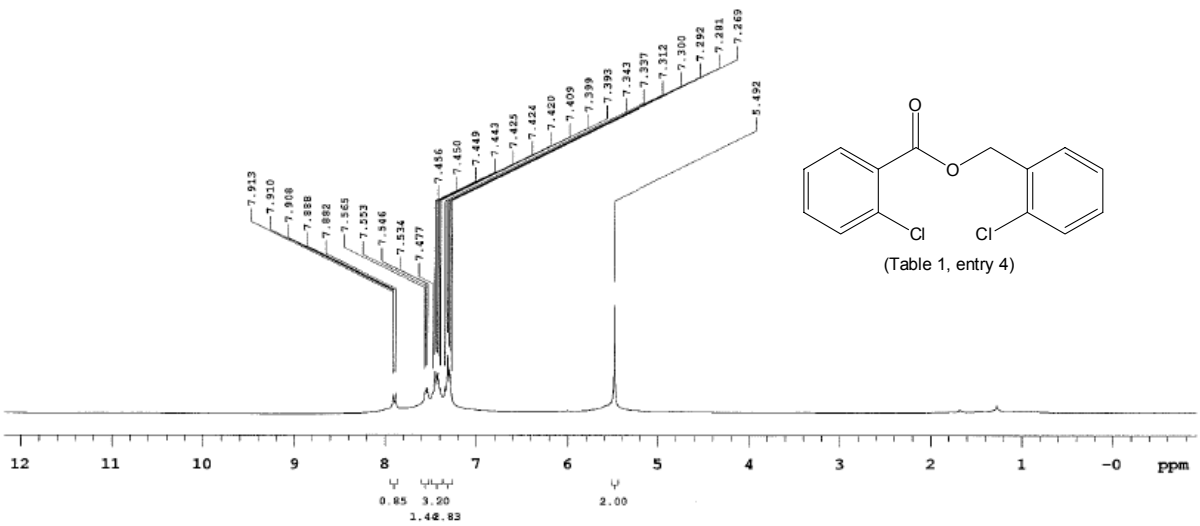


(Table 1, entry 5)



rk-F212-F-1H

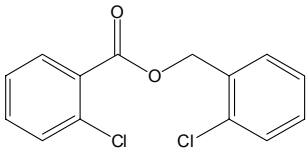
File: home/actual/data7/rk-F212-F-1H.fid



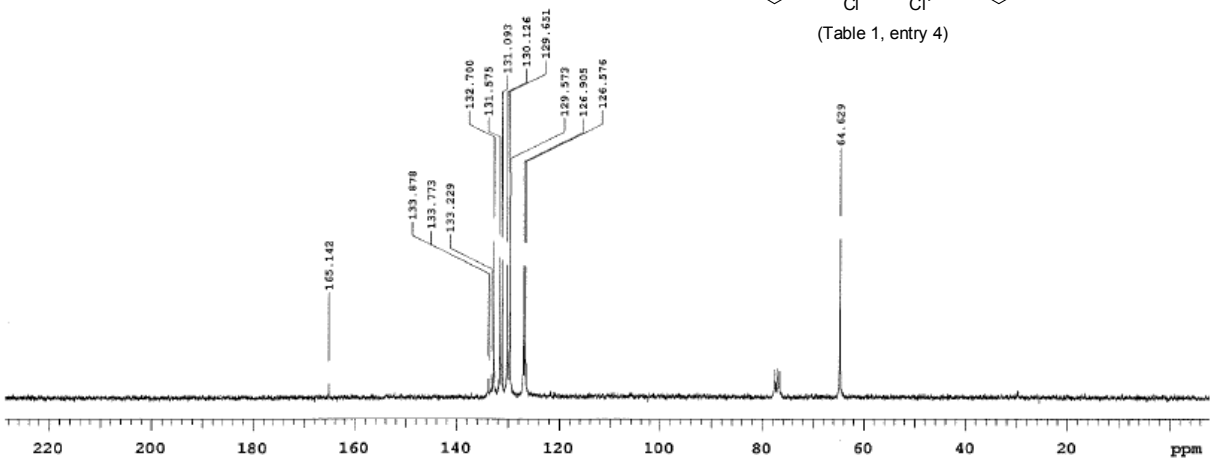
(Table 1, entry 4)

rk-F212-F-13C

File: home/actual/data7/rk-F212-F-13C.fid

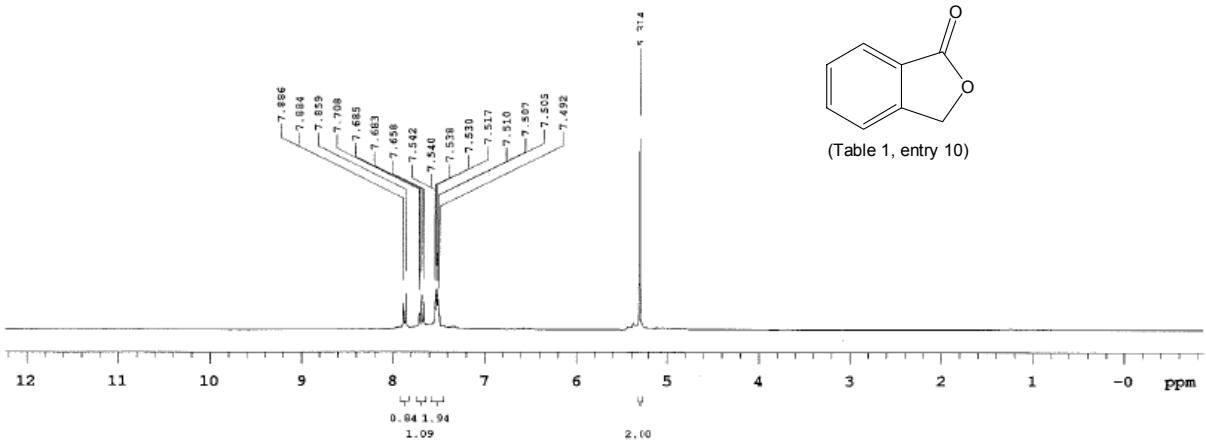


(Table 1, entry 4)



rk-E376-F-1H

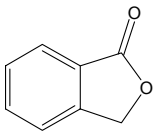
File: home/actual/data7/rk-E376-F-1H.fid



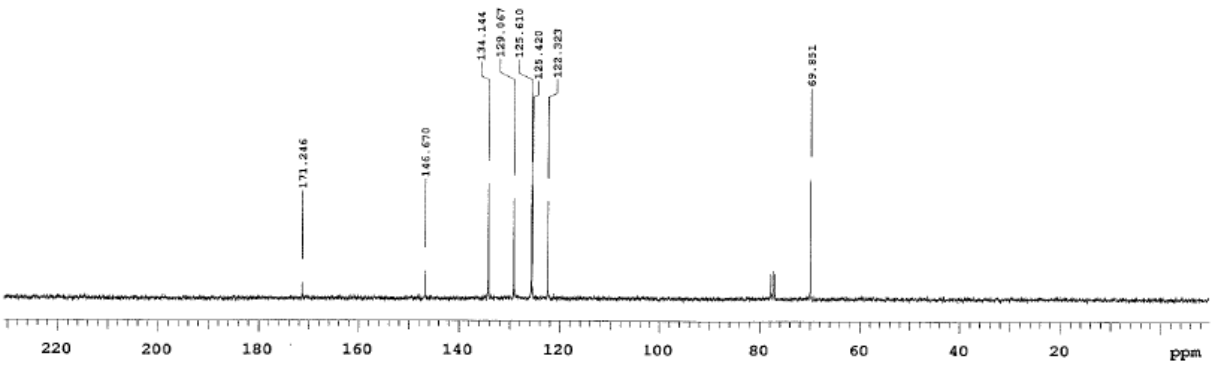
(Table 1, entry 10)

rk-E376-F-13C

File: home/actual/data7/rk-E376-F-13C.fid

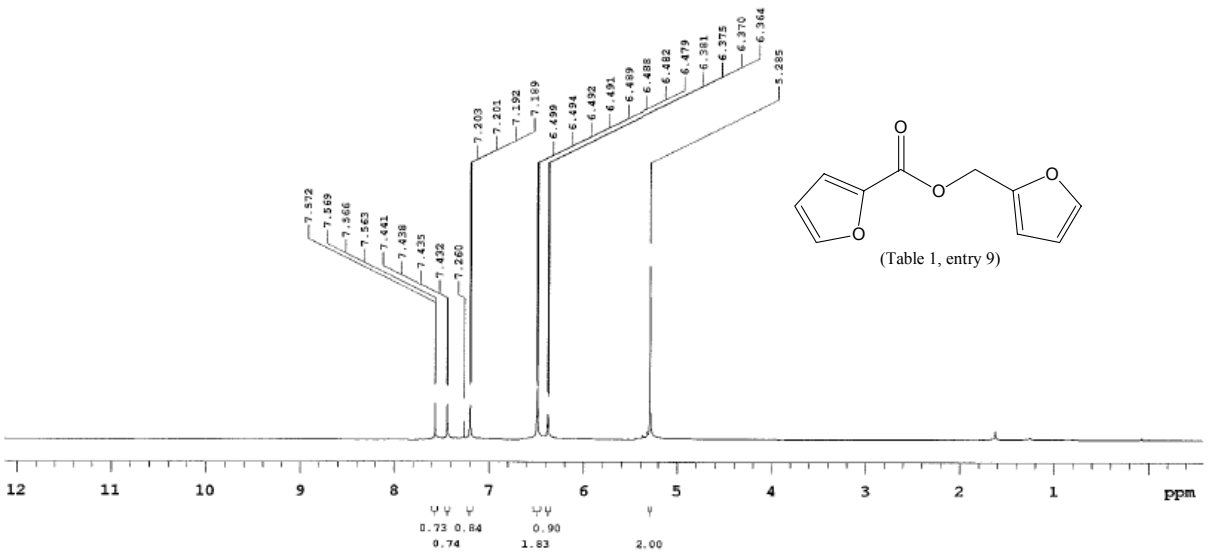


(Table 1, entry 10)



rk-E364-F-1H

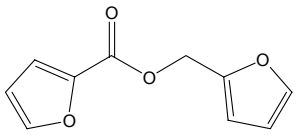
File: home/actual/data7/rk-E364-F-1H.fid



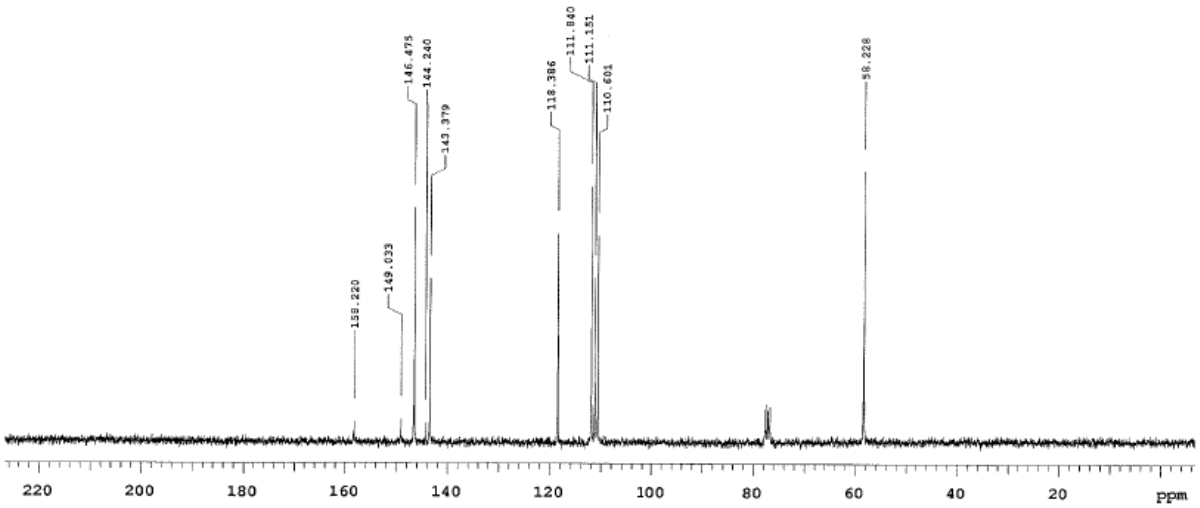
(Table 1, entry 9)

rk-E364-F-13C

File: home/actual/data7/rk-E364-F-13C.fid

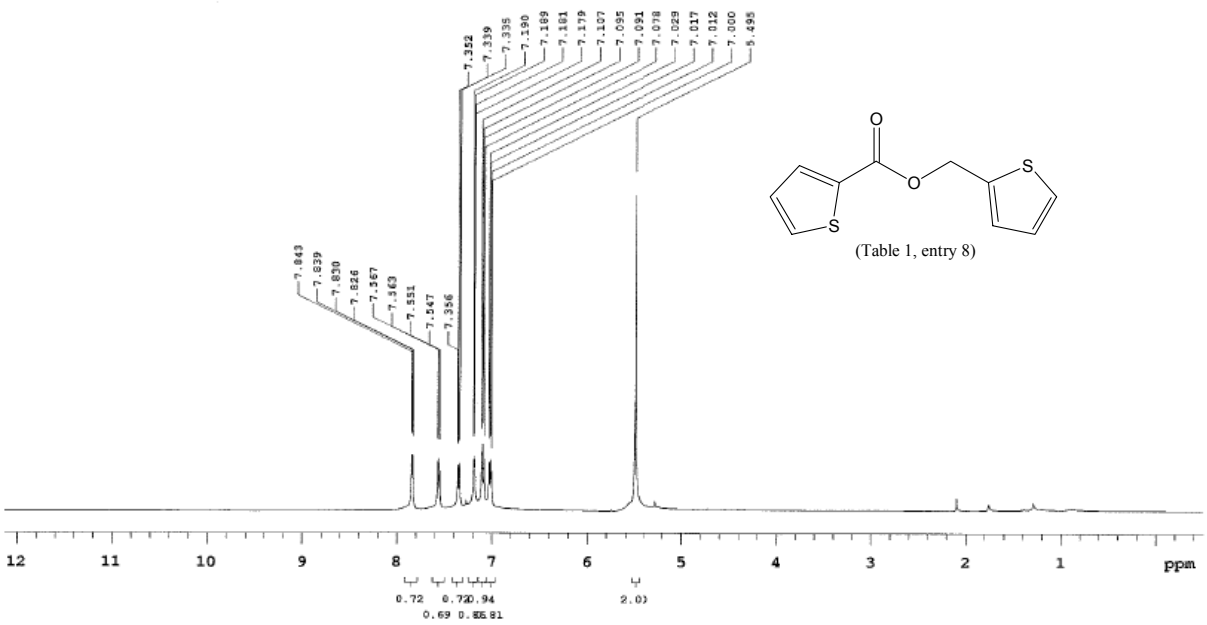


(Table 1, entry 9)



rk-E350-F-1H

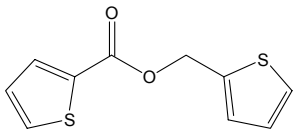
File: home/actual/data7/rk-E350-F-1H.fid



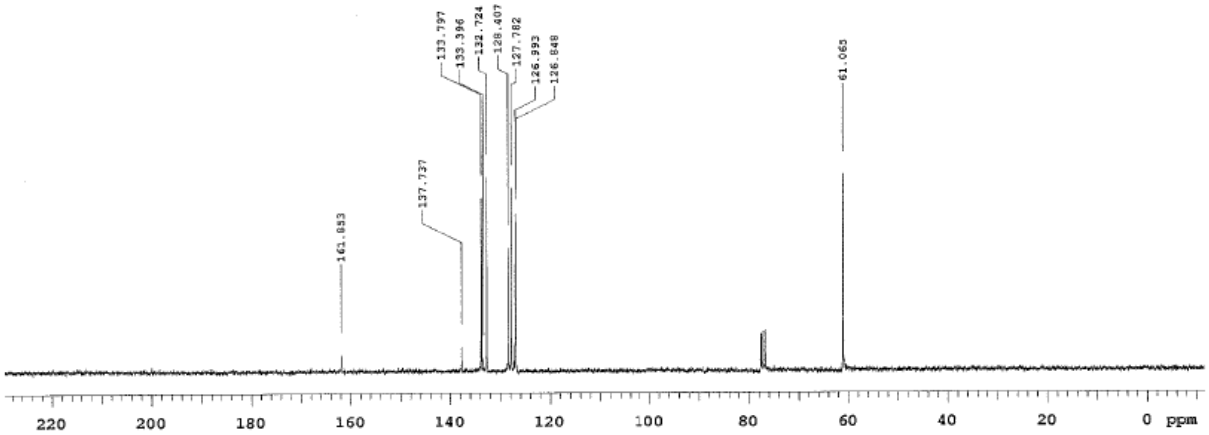
(Table 1, entry 8)

rk-E350-F-13C

File: home/actual/data7/rk-E350-F-13C.fid

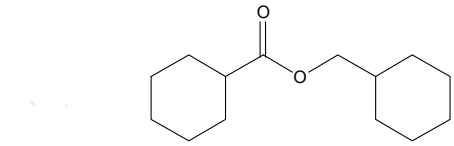


(Table 1, entry 8)



rk-E270-F-1H

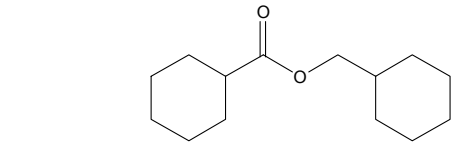
File: home/actual/data7/rk-F270-F-1H.fid



(Table 3, entry 9)

rk-E370-F-13C

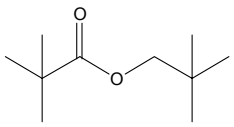
File: home/actual/data7/rk-F270-F-13C.fid



(Table 3, entry 9)

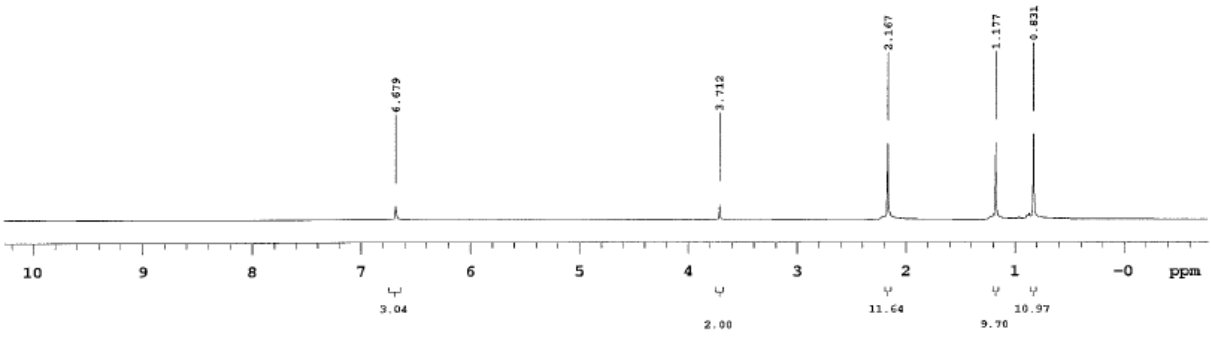
zk-F215-C-1H

File: home/actual/data7/zk-ZD-TMA-F2.fid



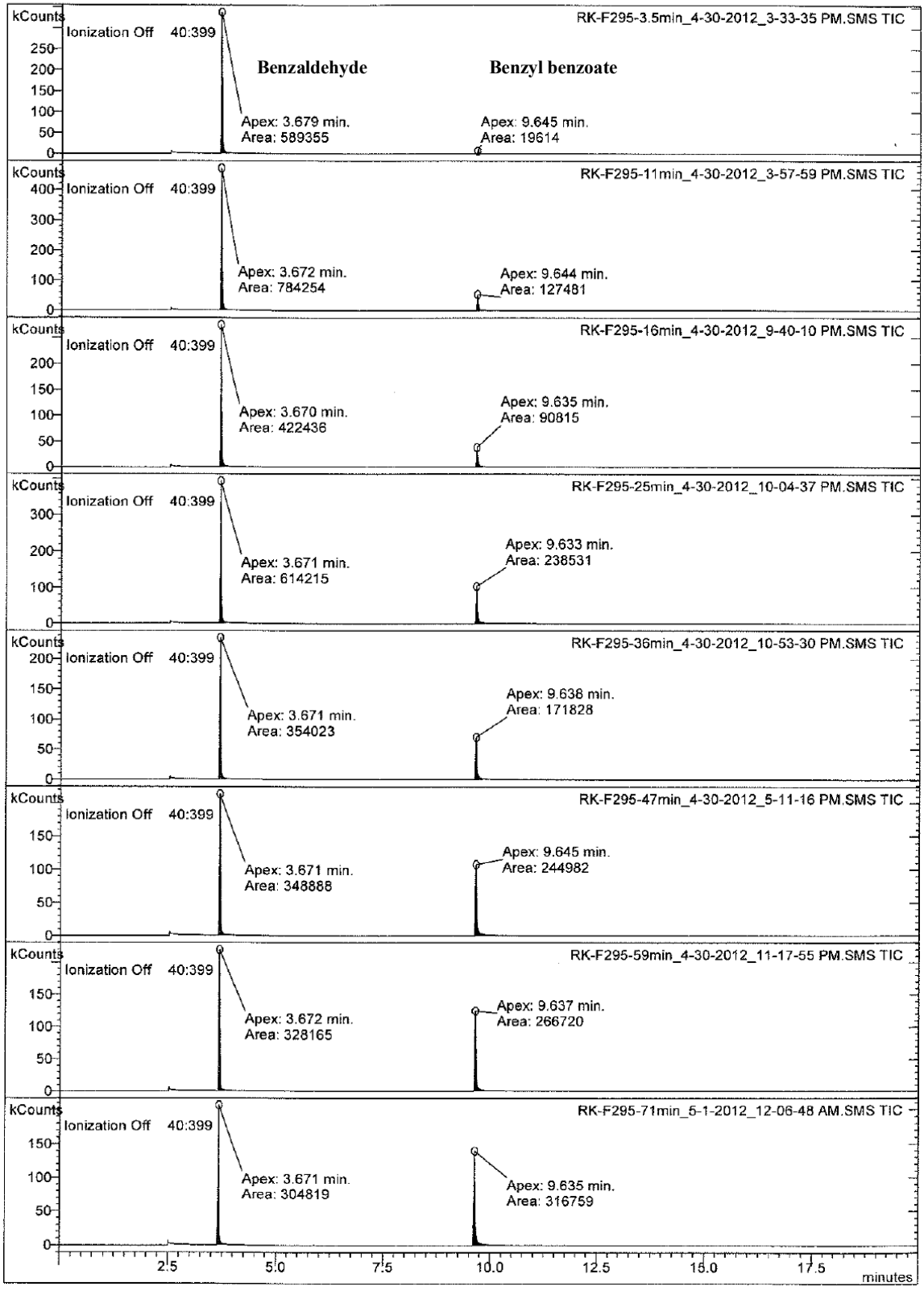
(Table 2, entry 13)

Crude spectra - Mesitylene as internal standard



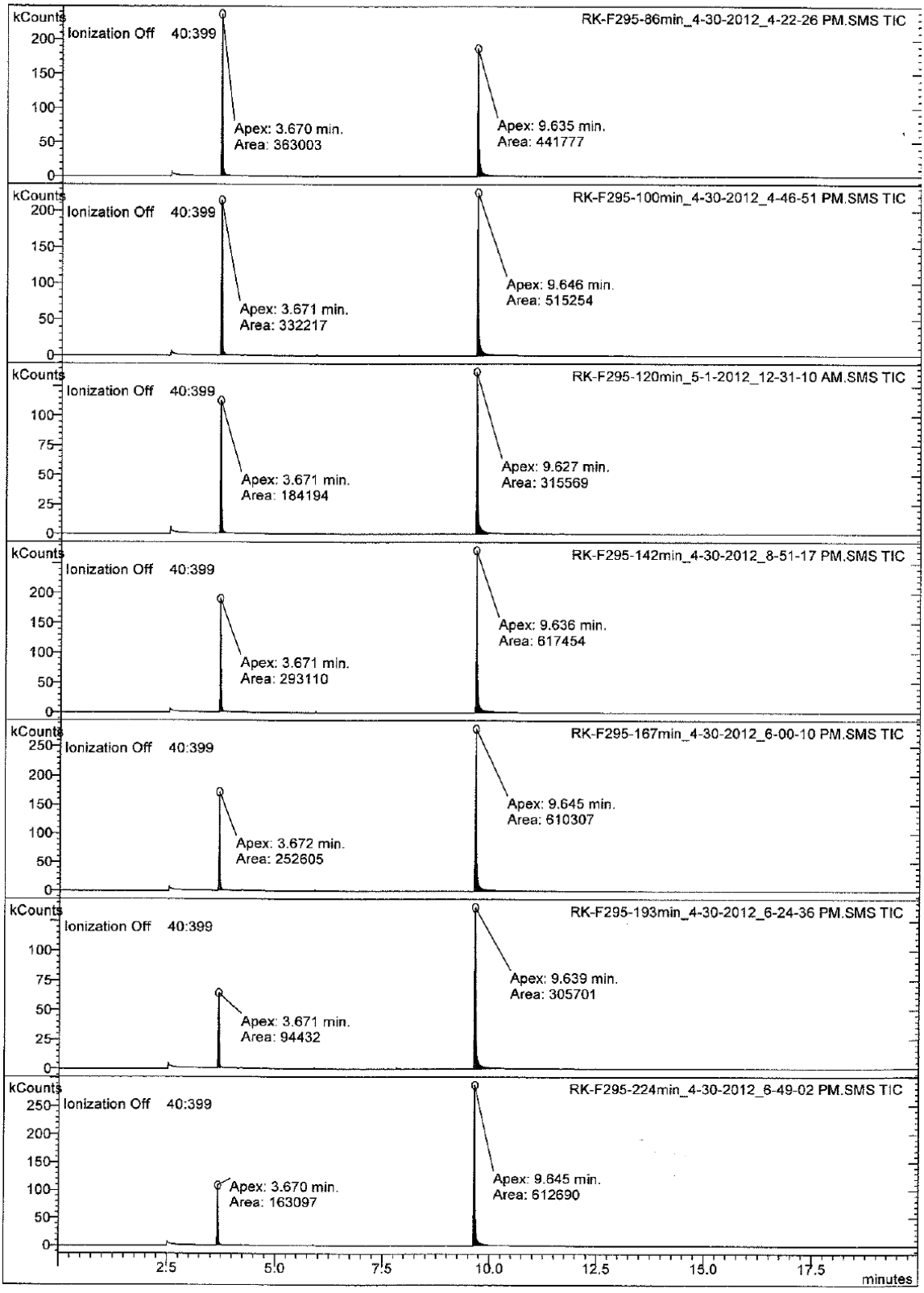
Chromatogram Plots

Kinetics of *t*-BuOK/Benzaldehyde



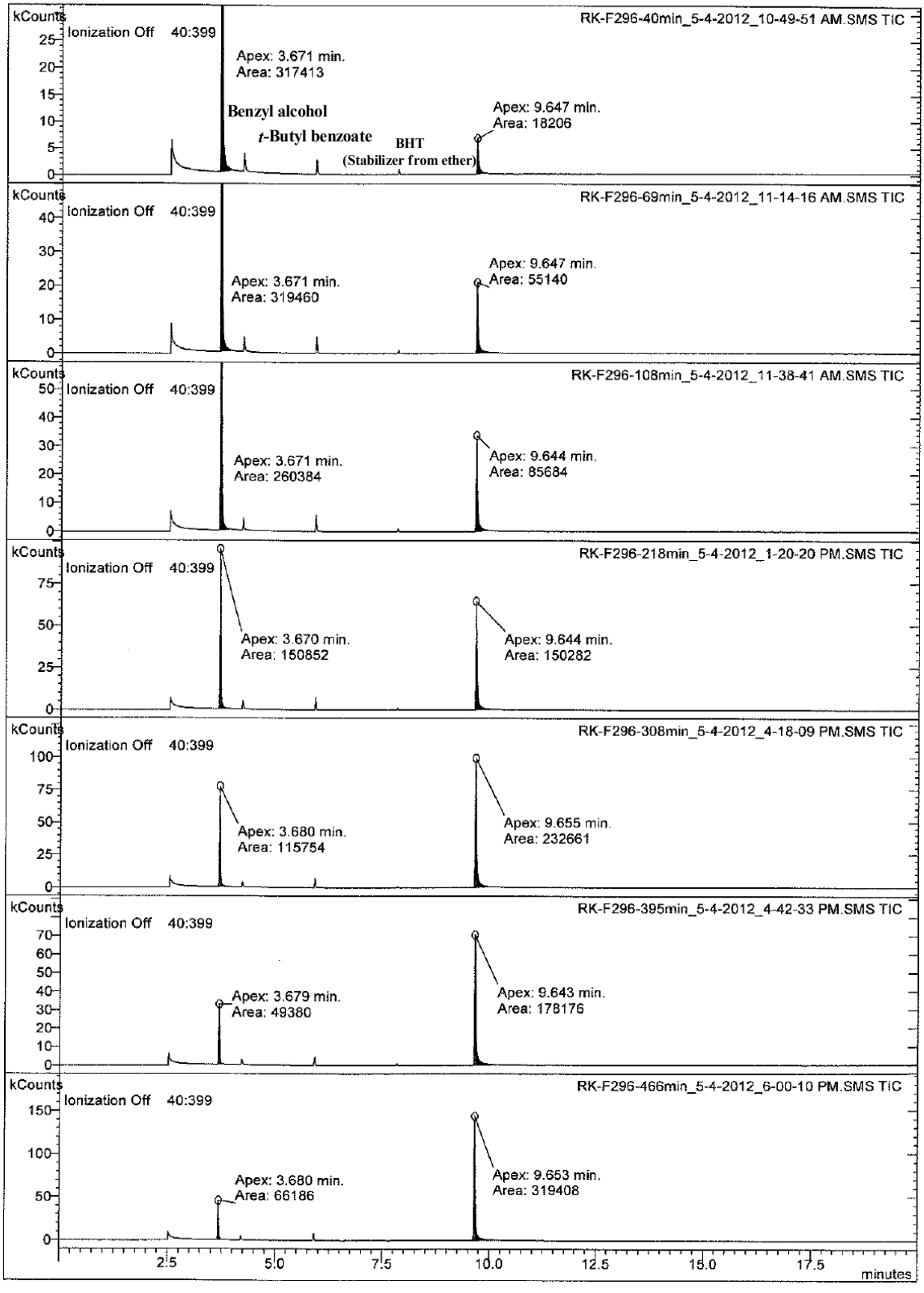
Chromatogram Plots

Kinetics of *t*-BuOK/Benzaldehyde continued...



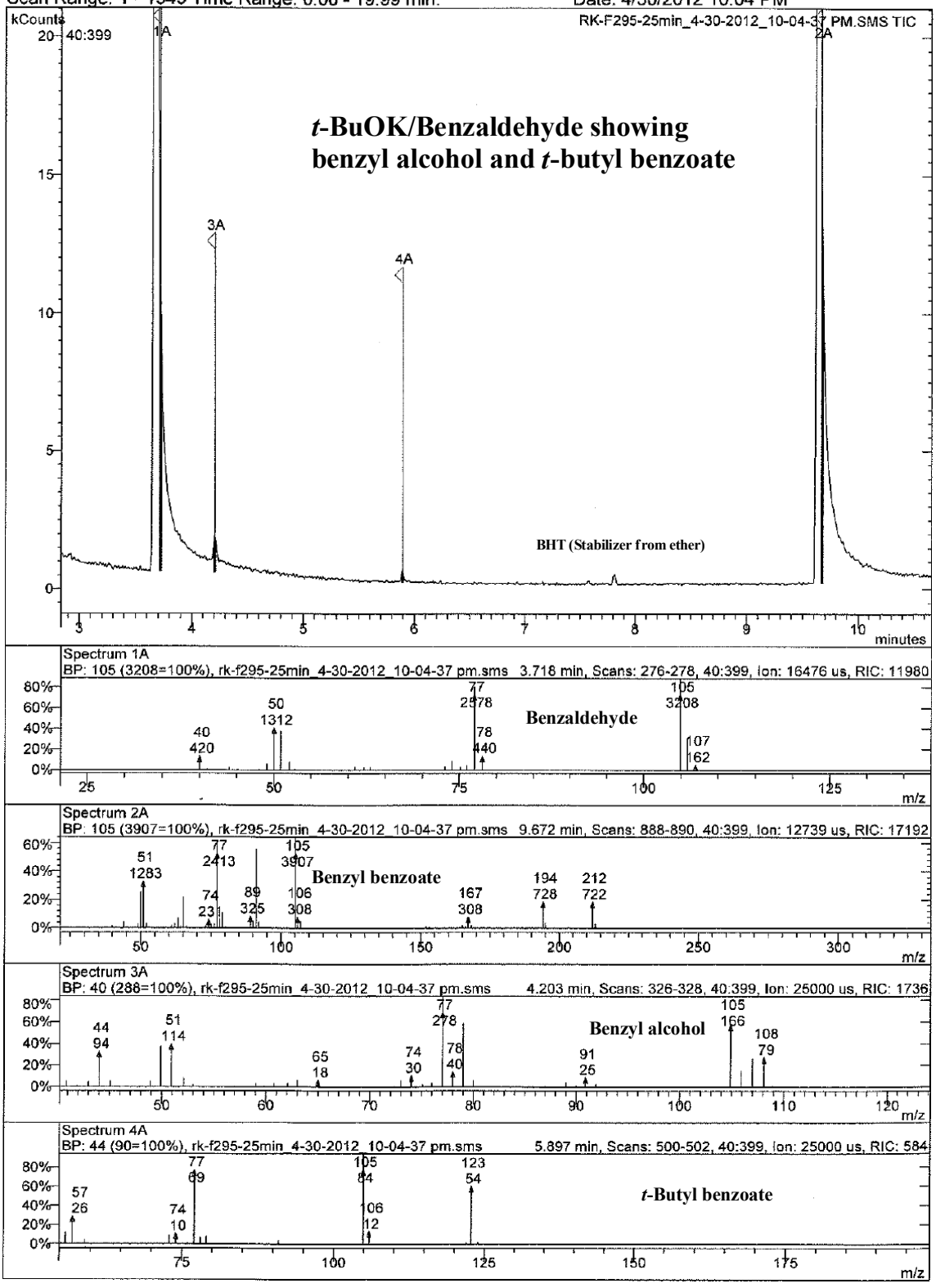
Chromatogram Plots

Kinetics of *t*-BuONa/Benzaldehyde



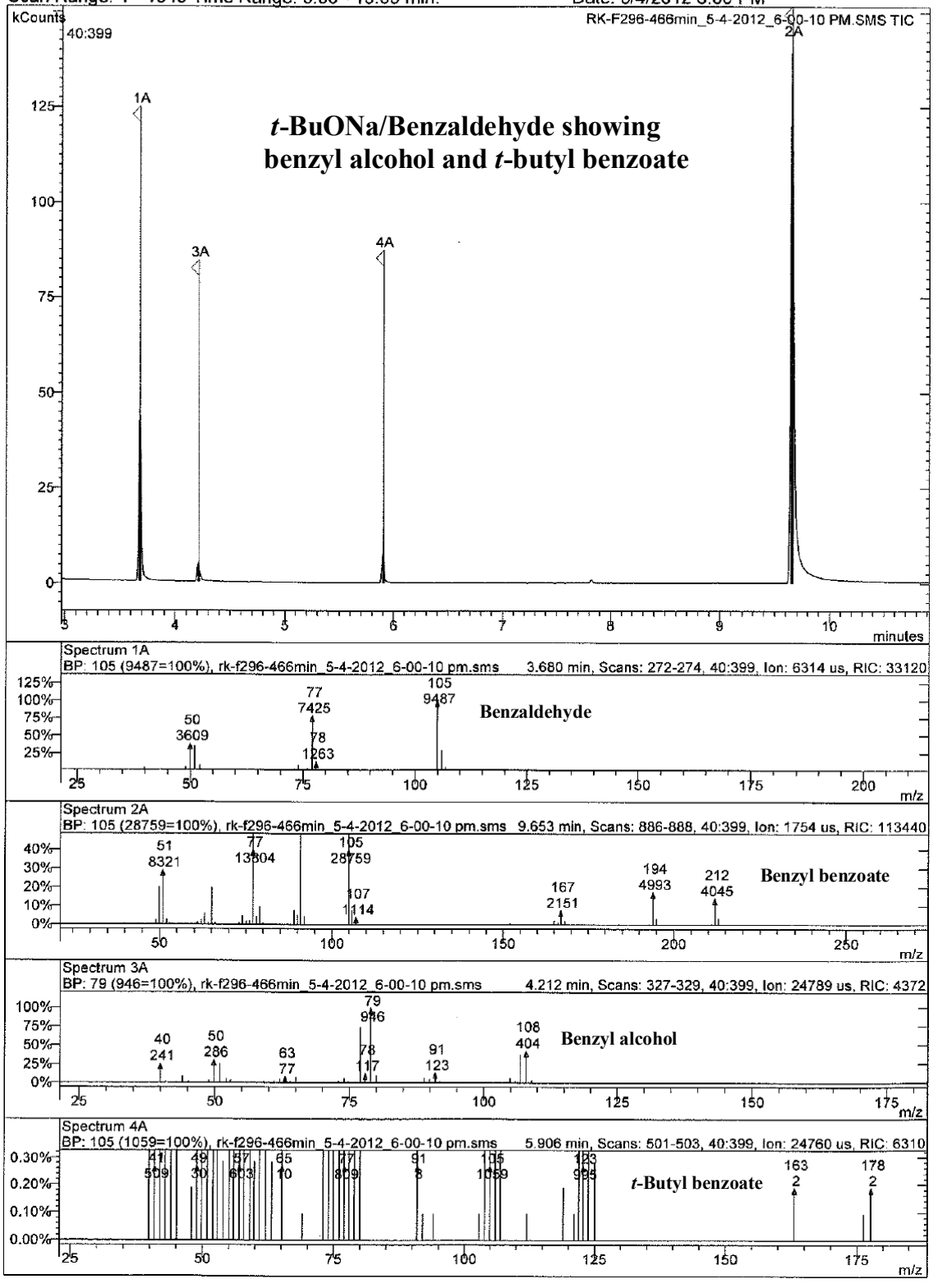
MS Data Review All Plots - 10/31/2012 5:24 PM

File: ...gs\administrator\desktop\rk\rk-f295-25min_4-30-2012_10-04-37 pm.sms
Sample: RK-F295-4 Operator: Manfred
Scan Range: 1 - 1949 Time Range: 0.00 - 19.99 min. Date: 4/30/2012 10:04 PM



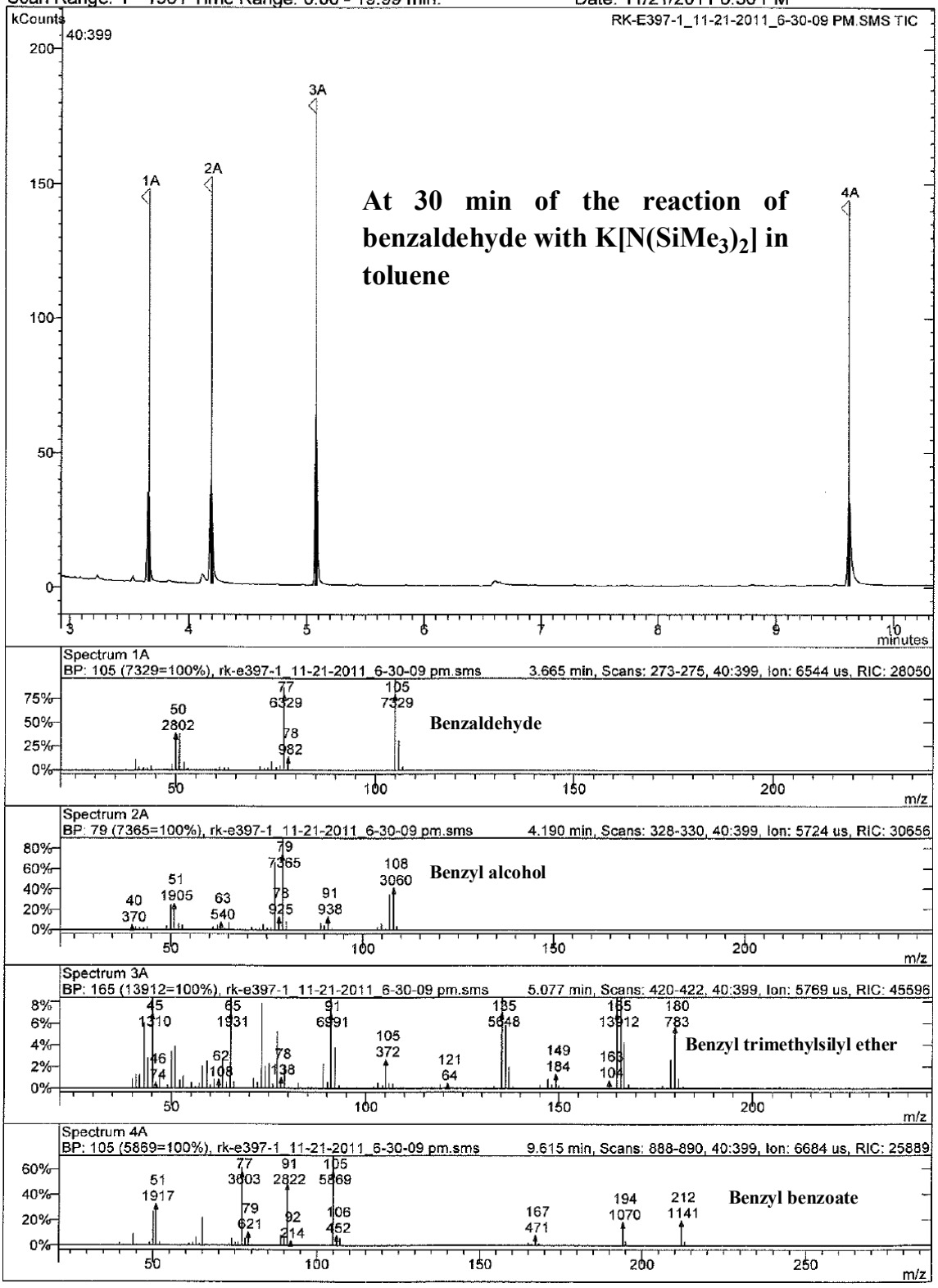
MS Data Review All Plots - 10/30/2012 9:02 PM

File: ...ngs\administrator\desktop\rk\rk-f296-466min_5-4-2012_6-00-10 pm.sms
Sample: RK-F296-9 Operator: Manfred
Scan Range: 1 - 1949 Time Range: 0.00 - 19.99 min. Date: 5/4/2012 6:00 PM



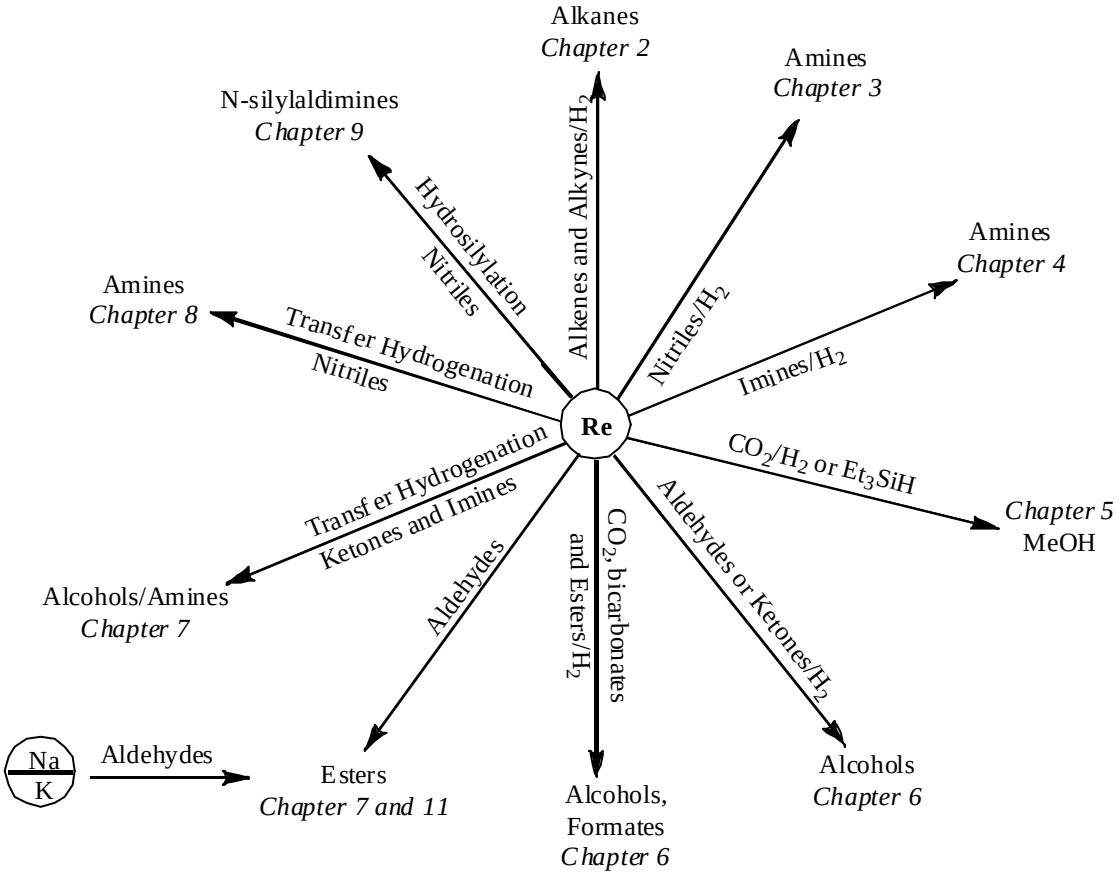
MS Data Review All Plots - 10/31/2012 3:45 PM

File: ...c-ms-tcd\gc-ms for aci\rajesh k\rk-e397-1_11-21-2011_6-30-09 pm.sms
Sample: RK-E397-1re
Operator: Manfred
Scan Range: 1 - 1961 Time Range: 0.00 - 19.99 min.
Date: 11/21/2011 6:30 PM



Summary

Novel class of large bite angle diphosphine nitrosyl rhenium complexes were prepared and their catalytic capabilities for hydrogenations and transfer hydrogenations of a variety of functionalities and hydrosilylations of nitriles, as well as Claisen-Tishchenko disproportionative esterification of aldehydes were realized. Alkali metal compounds catalyzed Claisen-Tishchenko Reactions were also discovered. Summarized schemes of these transformations are shown below.



Scheme 11.1. Summarizing scheme of hydrogenation and related transformations catalyzed by rhenium(I) complexes, as well as alkali metal compounds.

Chapter 1 of the thesis gives a general introduction and motivation for rhenium catalysis. Following this, Chapter 2 consists of preparation of appropriate rhenium complexes and their application to olefin hydrogenations. Large bite angle diphosphine ligands **A**, **B** and **C** (Figure 11.1) were used to prepare complexes of the type [Re(P∩P)(CH_3CN)Br_2(NO)] (P∩P = Sixantphos (**A**), **IIA**; P∩P = Sixantphos-Ph_2 (**B**), **IIB**; P∩P = Thixantphos (**C**), **IIC**), as well as the dinuclear complex [Re_2(**A**)$_2$$(Br)_2$(μ-$Br)_2$(NO)].2$CH_3CN$ (**IIIA**) were prepared. On

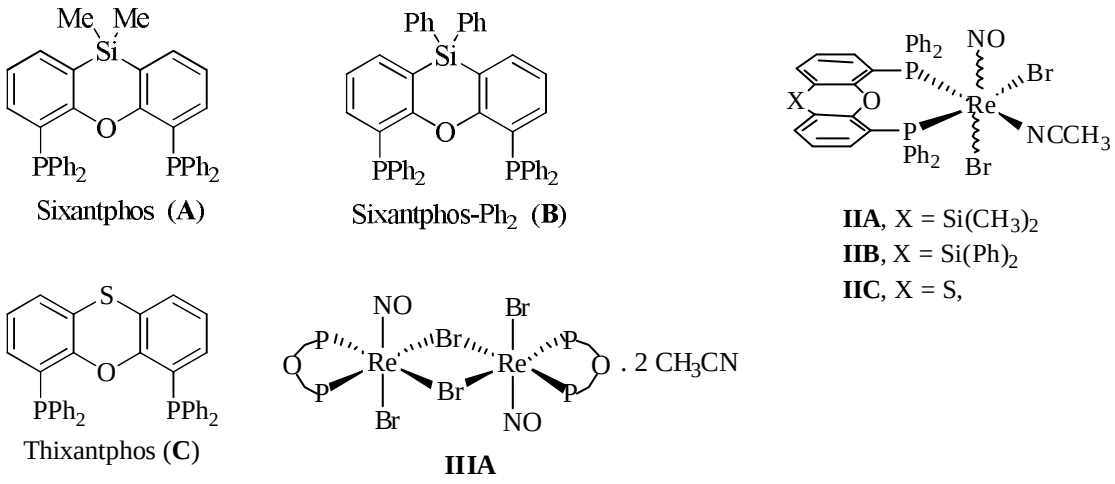


Figure 11.1. Ligands **A**-**C** and their nitrosyl rhenium complexes of the type **II** and **III**.

attempts to prepare complexes of the type [Re(P∩P)(η^2-ethylene)HBr(NO)] (**VIA** and **VIB**) by the reaction of **IIA-IIB** with Et_3SiH and ethylene, a reaction channel was discovered revealing orthometallation of one of the phenyl groups of the diphosphine ligand (Figure 11.2). Thus, four membered rhenacycles of the type [Re(oC_{PPh}-P∩P)(η^2-ethylene)Br(NO)] (**VIIA** and **VIIB**) were formed. **VIIA** and **VIIB** were composed of the isomers **VIIA1**, **VIIA2** and **VIIB, VIIB2,** respectively (Figue 11.2). These isomers were separated by column chromatography. When these orthometallated complexes were reacted with H_2, they underwent back reaction with hydrogenolysis of the Re-C_{PPh} bond leading to the transient formation of the **VIA** and **VIB** which were highly reactive in hydrogenations of olefins generating the coordinatively unsaturated active species of type [Re(P∩P)HBr(NO)] (**VA** and

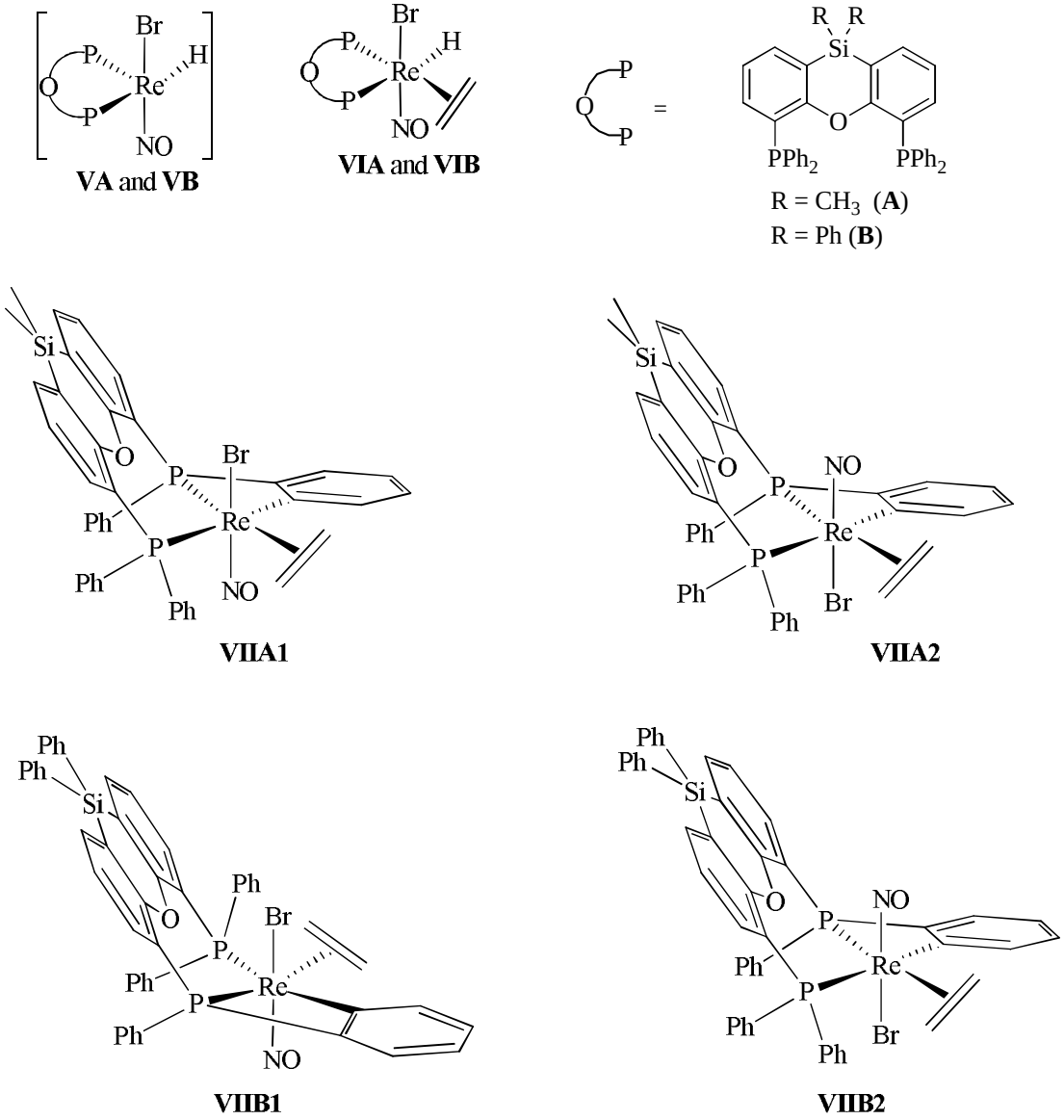
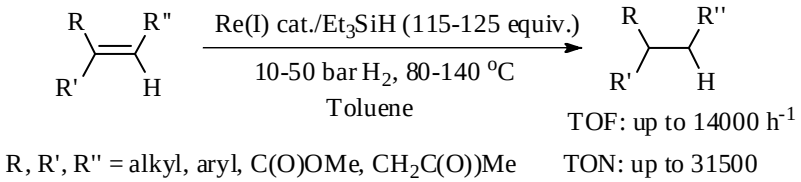


Figure 11.2. Complexes of types **V** (the active species in hydrogenations of olefins and hydrosilylations of nitriles), **VI** and **VII**.

VB).

All the complexes of type **II** and **IIIA,** as well as of type **VII** were found to be active catalysts in the hydrogenation of olefins in the presence or absence of an activating co-catalyst. For instance, using complex **IIIA** along with 115 equiv. of Et_3SiH as an activating co-catalyst TOFs up to 14000 h^{-1} could be achieved under a H_2 pressure of 10 bar at 120 °C in the hydrogenation of styrene. No loss of activity was observed in the hydrogenation of



Scheme 11.2. Hydrogenation of olefins catalyzed by complexes of type **II** and **IIIA,** as well as of type **VII**.

styrene giving complete conversion to ethyl benzene in TONs of up to 29900.

The complexes **IIB**, **VIIA** and **VIIB** were also found to be efficient catalysts for this transformation, but were less active when compared to complex **IIIA**. Olefins pocessing *β*-hydrogen atoms were found to be less active due to a prevailing isomerization reaction leading to internal olefins. Apart from styrene, all the following listed olefins were hydrogenated under different catalytic conditions using catalysts **VIIA1** and **VIIA2**. A few selected reactions are given: 1-hexene (cat. **VIIA1**, 10 bar H_2, 80 °C, TOF: 4867 h^{-1} (TON at 28% conv.)), cyclohexene (cat **VIIA2**, 10 bar H_2, 120 °C, TOF: 1231 h^{-1} (TON at 37% conversion)), α-methyl styrene (cat **VIIA2**, 10 bar H_2, 120 °C, TOF: 1940 h^{-1}, TON: 20025, 100%) and dimethyl itaconate (cat **VIIA1**, 10 bar H_2, 140 °C, TOF: 500 h^{-1}, TON: 31500, 95%)). The complex **VIIA** was tested also in the hydrogenation of an alkyne, phenylacetylene (50 bar H_2, 140 °C) which showed complete conversion to ethyl benzene in < 10 h when a loading of 0.043 mol% of it was adopted. A catalytic cycle operating for hydrogenation reactions of olefins using **II**, **IIIA** and **VII** is elucidated with the active species **V**. The diiodo complex [Re(POP)$(I)_2$(NO)] (**XIIIA**), where the O atom of Sixantphos ligand is coordinated *trans* to NO ligand, as well as [Re(**D**)$(Br)_2(CH_3CN)_2$(NO)] (**D** = DBFmonophos; **XIVD**) (Figure 11.3) were also prepared and studied their catalytic activity towards the hydrogenation of styrene. They furnished TOFs (first hour) of 8590 h^{-1}, TON:

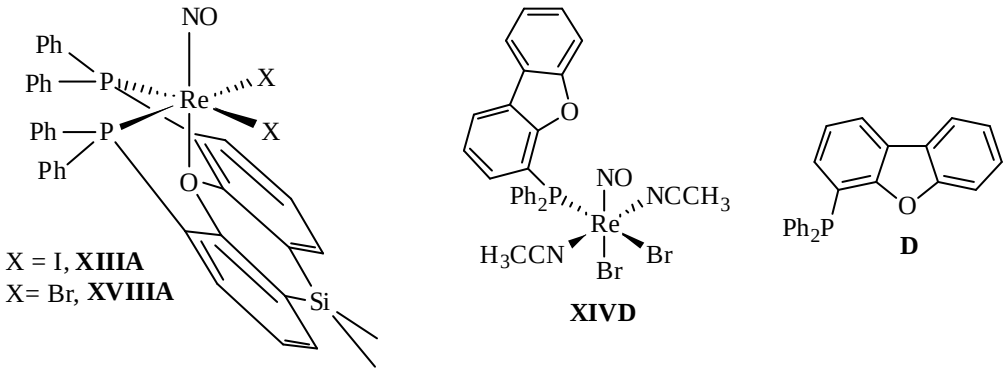
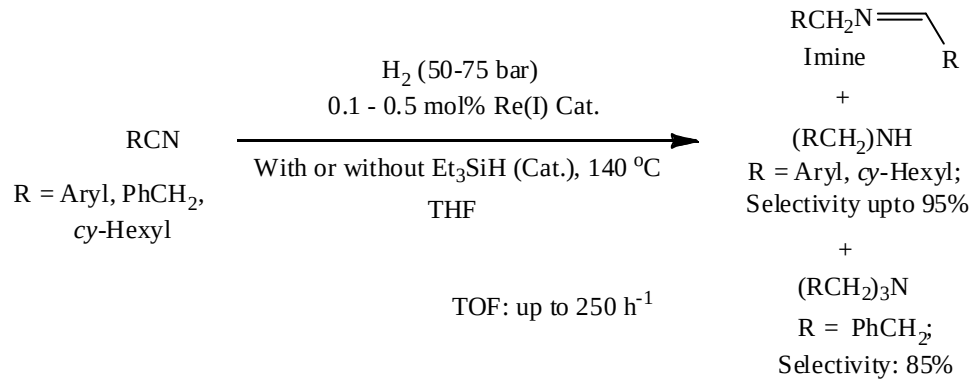


Figure 11.3. Rhenium complexes **XIIIA**, **XVIIIA** and **XIVD** as well as ligand **D**.

29000 and 2710 h^{-1}, TON: 21180, respectively, under a pressure of 10 bar of H_2 at 120 °C.

Reaction of complex **IIIA** with *n*-Bu_4NBr showed the formation of complex **XVIIIA** analogous to **XIIIA**. The opportunity of facile and easier access of the site *trans* to NO ligand by addition of *n*-Bu_4NBr is utilized in many transformations.

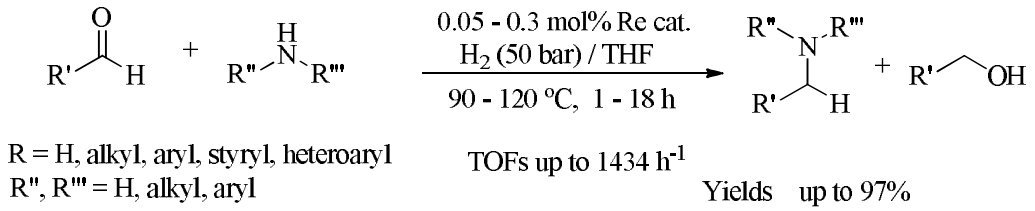
Chapter 3 describes the hydrogenations of nitriles which were carried out under a pressure of 50 or 75 bar of H_2 and at a temperature of 140 °C with a loading of 0.1-0.5 mol% of complexes **IIIA**, **IIB**, **VIIA** or **VIIB** along with the presence or absence of Et_3SiH as a co-catalyst (Scheme 11.3). These reactions showed selectivity towards formation of secondary or tertiary amines depending on the structure of the nitrile. Selected reactions include the hydrogenation of benzonitrile (**VIIA**, 0.1 mol%, 50 bar, 140 °C, TOF: 250 h^{-1} at 50% conv., 90%), 3-tolunitrile (**IIIA**, 0.5 mol%, 75 bar, 140 °C, TOF: 198 h^{-1}, 99%),



Scheme 11.3. Hydrogenation of nitriles using complexe **IIB**, **IIIA** and of the type **VII**.

2-thienylcarbonitrile (**VIIA**, 0.5 mol%, 75 bar, 140 °C, TOF (first h): 162 h^{-1}, 99%), and cyclohexanecarbonitrile (**IIIA**, 0.5 mol%, 50 bar, 140 °C, TOF: 198 h^{-1}, 99%) all showed selectivity towards the formation of secondary amines whereas phenyl acetonitrile showed selectivity towards the formation of tertiary amine (**VIIA**, 0.5 mol%, 50 bar, 140 °C, TOF (first h): 176 h^{-1}, 99%).

In Chapter 4, the complexes **IIB**, **IIIA** and of type **VII** and **XIIIA** were applied for the reductive aminations (Scheme 11.4) and hydrogenations of imines (Scheme 11.5).

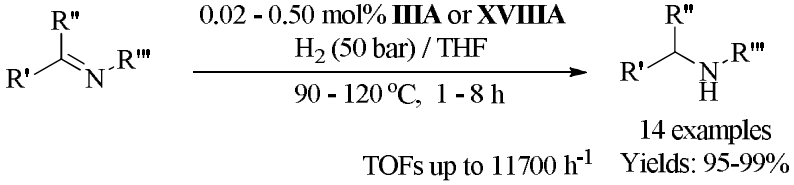


Scheme 11.4. Reductive amination of aldehydes catalyzed by complexes **IIB**, **IIIA** and of the type **VII**.

With aniline as amine, a variety of aldehydes were reductively aminated to furnish the desired secondary amines with good to excellent yields in most of the cases; selected examples using complex **IIIA** as catalyst with the condition of hydrogenation and TOF of the first hour include, benzaldehyde (0.05 mol%, 90 °C, TOF: 962 h^{-1}, 95%); 4-methoxybenzaldehyde (0.05 mol%, 90 °C, 1107 h^{-1}, 96%); 3-nitrobenzaldehyde (0.3 mol%, 120 °C, TOF: 171 h^{-1}, 94%), 4-chlorobenzaldehyde (0.15 mol%, 90 °C, TOF: 135 h^{-1}, 94%), 1-naphthaldehyde (0.2 mol%, 90 °C, TOF: 84 h^{-1}, 91%), 2-thienylcarboxaldehyde (0.05 mol%, 90 °C, TOF: 871 h^{-1}, 97%), *trans*-cinnamaldehyde (0.1 mol%, 90 °C, TOF: 309 h^{-1}, 66%). Reductive amination of benzaldehyde with 4-iodoaniline using 0.05 mol% of **IIIA** at 90 °C showed the desired product with a TOF of 1434 h^{-1} in the first hour, but prolonged run of this reaction led to deiodinated product, *N*-benzylaniline in 90% yield. Under these

conditions, 4-nitroaniline showed a TOF of 376 h^{-1} in in the first hour giving rise to 97% yield of the desired product in 9 h. A concomitant hydrogeneation of formaldehyde to methanol was observed wherever it was used for reductive amination. Reductive amination of hexanal with 1-hexylamine (120 °C, TOF: 37 h^{-1} (first hour)) giving rise to a yield 76% of the desired product when a loading 0.2% of **IIIA** was adopted). Since formation of imines is not possible with secondary amines, their reductive alkylation gave lower yields due to the prevailing hydrogenation of the aldehydes to their corresponding alcohols.

In contrast to the reductive amination reactions, the hydrogenations of amines were highly efficient. The activity of the complex **IIIA** in the hydrogenations of various imines is as follows. N-benzylideneaniline (0.02 mol%, 90 °C, TOF (first 0.25 h): 3900 h^{-1}, 97%); N-(4-methoxybenzylidene)aniline (0.02 mol%, 90 °C, TOF (first 0.25 h): 11700 h^{-1}, 97%);



Scheme 11.5. Hydogenation of imines catalyzed by **IIIA** and of the type **VII**.

N-(4-nitrobenzylidene)aniline (0.5 mol%, 120 °C, >192 h^{-1}, 96%); N-(4-fluorobenzylidene)aniline (0.1 mol%, 90 °C, TOF (first 0.25 h): 2070 h^{-1}, 99%); N-(4-chlorobenzylidene)aniline (0.1 mol%, 90 °C, TOF (first 0.25 h): 1012 h^{-1}, 97%); N-benzylidene-4-nitroaniline (0.1 mol%, 90 °C, >330 h^{-1}, 99%), N-benzylidene-4-fluoroaniline (0.1 mol%, 90 °C, TOF (first 0.25 h): 2810 h^{-1}, 99%); N-benzylidene-4-chloroaniline (0.1 mol%, 90 °C, TOF (first 0.25 h): 1555 h^{-1}, 98%), N-benzylidene-4-methoxyaniline (0.02 mol%, 90 °C, TOF (first 0.25 h):: 7760 h^{-1}, 98%, 98%), N-(4-methoxybenzylidene)-4-chloroaniline (0.02 mol%, 90 °C, >2425 h^{-1}, 97%), N-benzylidene-1-naphthylamine (0.15

mol%, 120 °C, 950 h^{-1}, 95%), N-benzylidene-1-hexylamine (0.1 mol%, 120 °C, 106 h^{-1}, 95%), N-benzylidene-isobutylamine (0.15 mol%, 120 °C, 79 h^{-1}, 95%), N-(1-Phenylethylidene)aniline (0.5 mol%, 90 °C, > 198 h^{-1}, 99%).

The reductive anilation of benzaldehyde using 0.02 mol% of **IIIA** in the presence of 100 equiv. of *n*-Bu_4NBr with respect to **IIIA**, (which would form **XVIIIA**) was carried out at 90 °C showing a TOF of 8122 h^{-1} in the first 0.25 h, giving rise to a yield of 97% of the desired product, N-benzylaniline in 97% yield within an hour. The reductive anilation of benzaldehyde using 0.02 mol% of **XIIIA** under the conditions of 50 bar of H_2 at 90 °C showed a TOF of 2200 h^{-1} in the first 0.25 h giving rise to 97% yield of the desired product N-benzylaniline within 4 h.

From mechanistic studies, a catalytic cycle with **XXIA** as the active species is proposed for this hydrogenation of imines. It is formed by the dissociation of a bromide ligand followed by isomerisation, leading to the accessibility of the site *trans* to NO ligand. A

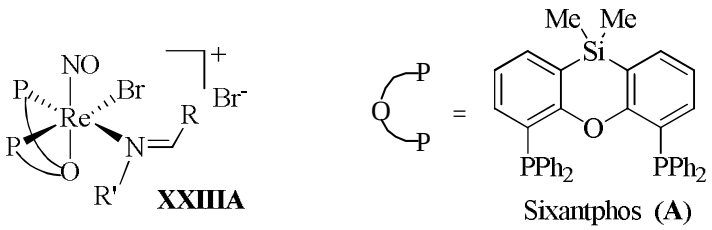
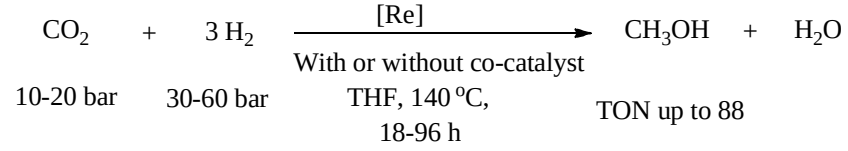


Figure 11.4. The active species **XXIA** in the hydrogenation of imines.

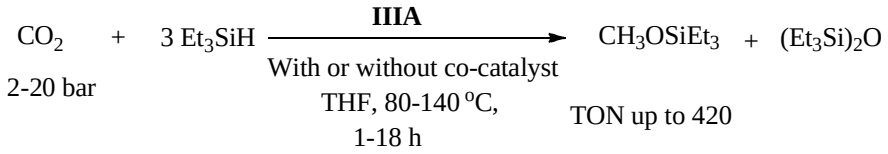
hydride ligand *trans* to NO ligand is much more hydridic in character and would eventually lead to transfer of it to the polar substrates.

In Chapter 5, complex **IIIA** in the presence or absence of *n*-Bu_4NBr (5 eqiuv. with respect to **IIIA**) as co-catalyst was applied also for the hydrogenation of carbon dioxide giving methanol in TONs of up to 88 at a pCO_2 : pH_2 = 20 : 60 at 140 °C run for 18 h (Scheme 11.6). Complexes [Re(**A**)$(Br)_3(NO)$][NEt_4] (**XIXA**) and [Re_2(**A**)$_2\mu$-$(OH)_3(NO)_2$]

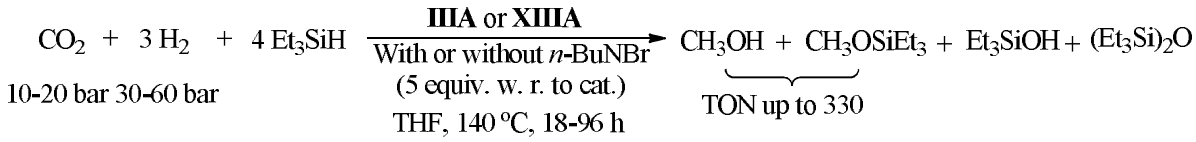
(**XXVA**) were also prepared (Figure 11.6). These complexes were then applied in the hydrogenation of CO_2 furnishing TON of 7 and 20 respectively under a $pCO_2 : pH_2 = 10 : 30$



Scheme 11.6. Hydrogenation of carbon dioxide to methanol catalyzed by complexes **IIIA**, **XIIIA**, **XIXA** and **XXVA**.



Scheme 11.7. Hydrosilylation of carbon dioxide to methanol level using complexes **IIIA** or **XVIIA**.



Scheme 11.8. Combined hydrogenations/hydrosilylation of carbon dioxide to methanol level using complexes **IIIA** or **XVIIA**

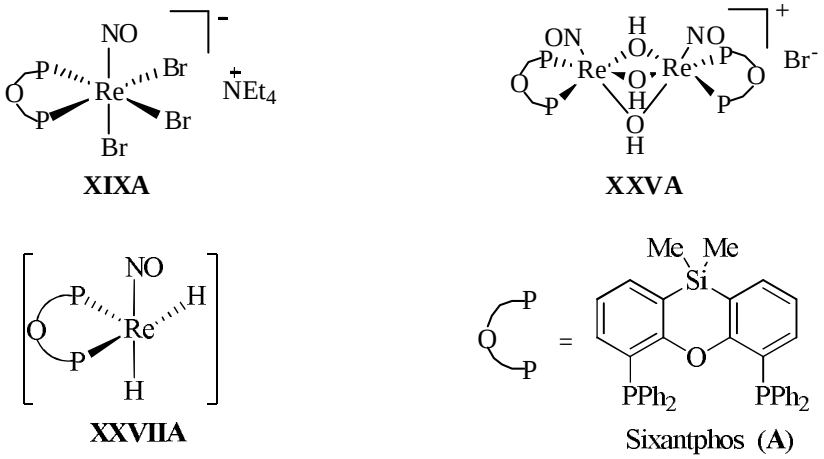
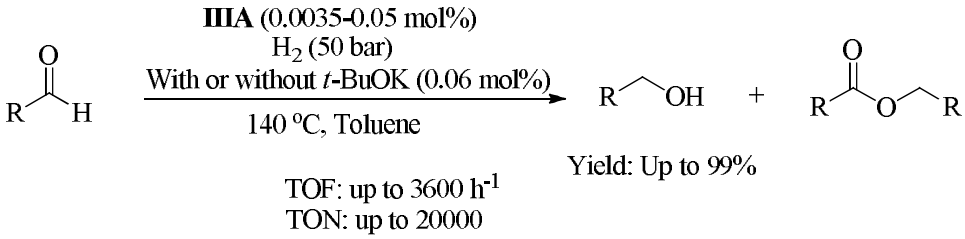


Figure 11.6. Complexes **XIXA** and **XXVA**, and the active species **XXVIIA** in the transfer hydrogenation reactions of ketones, imines and nitriles as well as hydrogenation/hydrosilylation reactions of CO_2 (right).

at 140 °C run for 18 h. The hydrosilylation of CO_2 with Et_3SiH (1000 equiv. with respect to catalyst) furnished CH_3OSiEt_3 with TONs of up to 420. Also, a combined hydrogenation/hydrosilylation (pCO_2 : pH_2 = 20 : 60, 100 equiv. of Et_3SiH) of carbon dioxide to methanol was also realized giving TONs up to 330 when run for 96 h at 140 °C (Scheme 11.7). The mechanism of these reactions of hydrogenation of CO_2 is proposed to be operated through the active species **XXVIIA** (Figure 11.6).

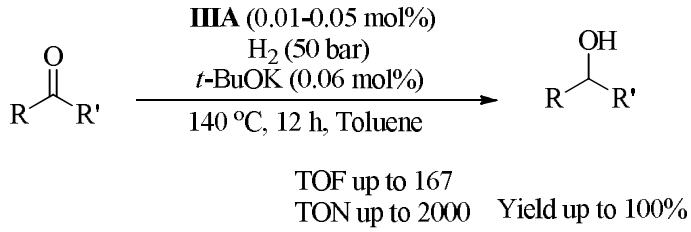
In Chapter 6, the hydrogenation reaction has also been extended to aldehydes, ketones, esters and bicarbonates giving rise to the corresponding alcohols (Scheme 11.9). TOFs of up to 4500 h^{-1} and TONs of up to 19200 with 99% yield were realized at 50 bar H_2 pressure and at 140 °C for the hydrogenation of aldehydes. Selected examples of hydrogenation of aldehydes with catalyst loading, TOFs and yield are as follows: benzaldehyde (0.005 mol%, 2133 h^{-1}, 96%);



Scheme 11.9. Hydrogenation of aldedhydes catalyzed by **IIIA**.

p-anisaldehyde (0.005 mol%, 2857 h^{-1}, > 99%); 4-chlorobenzaldehyde (0.02, 1250 h^{-1}, > 99%), 2-thiophenecarboxaldehyde (0.02 mol%, 1125 h^{-1}, 95%); cyclohexanecarboxaldehyde (0.02, 3920 h^{-1}, 98%), hexanal (0.02, 4500 h^{-1}, 90%); paraformaldehyde (0.05, 9 h^{-1}, 11%); trans-cinnamaldehyde (0.05, 960 , 96%).

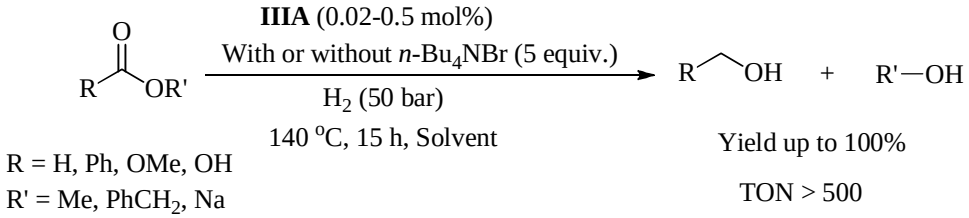
Under the same conditions, but with a loading of 0.05 mol% of **IIIA**, the hydrogenation reaction of ketones were also carried out (Scheme 11.10). As expected, the



Scheme 11.10. Hydrogenation of ketones catalyzed by **IIIA**.

efficiencies of TOF and yields of the tested ketones are as follows: acetophenone (167 h^{-1}, 100%), benzophenone (50 h^{-1}, 30%), 4′-fluoroacetophenone (162 h^{-1}, 97%), 2-acetylthiophene (23 h^{-1}, 14%). The aliphatic ketone, cyclohexanone gave a yield of only <5% in 12 h due to a concomitant aldol reaction.

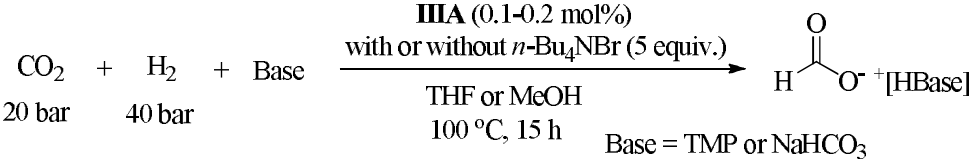
The hydrogenation of methyl formate to methanol could be realized with TON of 112 in THF when a catalyst loading of 0.5 mol% was adopted under a H_2 pressure of 50 bar at 140 °C (Scheme 11.11). Benzyl benzoate with the addition of *n*-Bu_4NBr furnished benzyl alcohol with a TON of 500. Under these conditions, but in EtOH, dimethyl carbonate provided a TON of 161. The hydrogenation of sodium bicarbonate to methanol in TON of 20 could be achieved for the first time when the reaction was carried out in EtOH in the presence of *n*-Bu_4NBr as a co-catalyst. Also, this reaction furnished sodium formate in TON of 24.



Scheme 11.11. Hydrogenation of esters and bicarbonates to alcohols using complex **IIIA**.

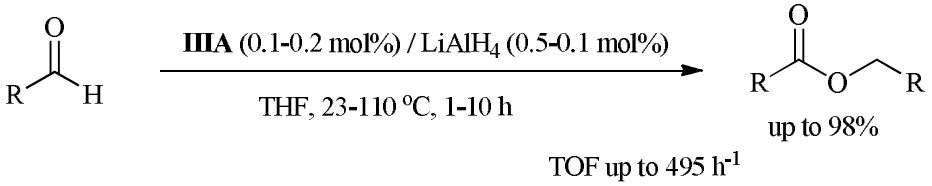
Using **IIIA** as a catalyst, the hydrogenations of CO_2 to formate salts were also realized with 2,2,6,6-tetramethylpiperidine (TMP) or $NaHCO_3$ as base under a relatively

lower temperature of 100 °C (Scheme 11.12). Overall TON of up to 605 could be realized when sodium bicarbonate was used as a base in the presence of 5 equiv of *n*-Bu_4NBr in MeOH.



Scheme 11.12. Hydrogenation of carbon dioxide to formate salts using **IIIA**.

In Chapter 7, Claisen-Tishchenko disproportionative esterification of aldehydes and transfer hydrogenations of ketones and imines were described. Highly efficient Claisen-Tishchenko disproportionations of benzaldehyde to benzyl benzoate were realized with a loading of 0.05 mol% of **IIIA** along with suitable silyl hydrides as a co-catalyst. Though an extensive optimization of this reaction showed TOFs of up to 3360 h^{-1} and yields up to 88%, concomitant hydrosilylations were always observed which retarded the reaction. However, the Claisen-Tishchenko reaction could be realized using complex **IIIA** along with $LiAlH_4$ as a co-catalyst (Scheme 11.13). Complex **IIIA** along with 5 equiv. of $LiAlH_4$ with respect to **IIIA**, eventually generated the species **XXVIIA**. With a loading of 0.1 or 0.2 mol% of **IIIA** along with 1 mol% of $LiAlH_4$, though the reaction of aromatic aldehydes were carried out at elevated temperatures of 80 °C or 110 °C, aliphatic aldehydes were smoothly converted to

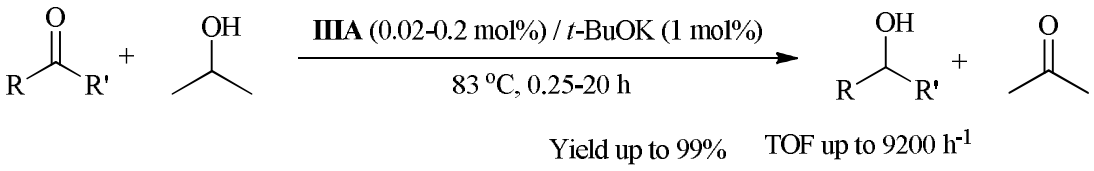


Scheme 11.13. Claisen-Tishchenko reaction of aldehydes catalyzed by **IIIA**/$LiAlH_4$ system.

their corresponding carboxylic esters at room temperature, furnishing yields of 90-98%. However, the reaction of paraformaldehyde furnished a yield of only 24% of the desired ester methylformate with a TOF of 120 h^{-1}. For each substrates, the reaction temperature, TOFs (first hour) and yield of the desired ester are as follows; benzaldehyde (80 °C, 260 h^{-1}, 97%); 4-chlorobenzaldehyde (110 °C, 275 h^{-1}, 96%); *p*-anisaldehyde (110 °C, 495 h^{-1}, 99%); 2-thienylcarboxaldehyde (110 °C, 391 h^{-1}, 97%); 2-furancarboxaldehyde (110 °C, 150 h^{-1}, 90%); hexanal (23 °C, 490 h^{-1}, 98%); isobutyraldehyde (23 °C, 465 h^{-1}, 93%); cyclohexanecarboxaldehyde (23 °C,435 h^{-1}, 96%); H (110 °C, 120 h^{-1}, 24%).

Based on experimental studies, a mechanism involving the generation of rhenium dihydrides **XXVIIA** followed by rhenium alkoxide as the active species is proposed.

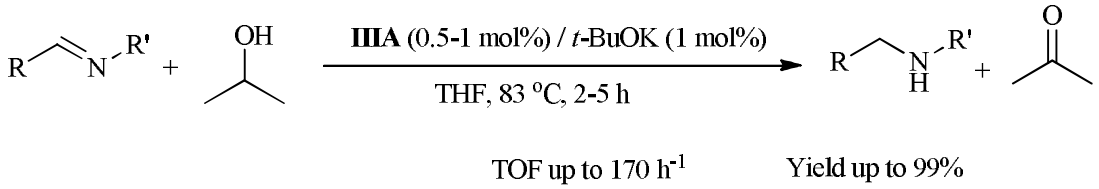
Following this, highly efficient transfer hydrogenation reactions of ketones and imines were also realized using 0.02-0.2 mol% of **IIIA** along with *t*-BuOK at 83 °C (Scheme 11.14 and Scheme 11.15). For instance, with a loading of 0.02 mol% of **IIIA** along with 1 mol% of *t*-BuOK at 83 °, acetophenone showed an initial TOF of 9200 h^{-1} with 46% conversion in 0.25 h. Yields of up to 95% were realized in the transfer hydrogenations of ketones. The activity of the complex **IIIA** towards this reaction is summarized as; ketone: (TOF (first 0.25 h), yield); acetophenone: (9200 h^{-1}, 89%); 4′-methoxyacetophenone: (6191 h^{-1}, 66%); 4′-methylacetophenone: (1529 h^{-1}, 82%); 4′-chloroacetophenone: (6090 h^{-1}, 76%); 2-acetylthiophene: (3568 h^{-1}, 66); benzophenone: (3554 h^{-1}, 95%); 3,3'-bis(trifluoromethyl)benzophenone: (1061 h^{-1}, >99%); Cyclohexanone: (2560 h^{-1}, 99%);



Scheme 11.14. Transfer hydrogenation of ketones catalyzed by **IIIA**/*t*-BuOK/2-propanol system.

2-cyclohexenone: (2108 h^{-1}, 74% (cyclohexanol as the product)).

Relatively higher loadings of 0.5 mol% of **IIIA** along with 1 mol% of *t*-BuOK were applied for the hydrogenation of aromatic aldimines giving up to 99% yield of the desired products (Scheme 11.14). This reaction was found to be less efficient for aliphatic imines. However, imine bearing an aliphatic part, N-benzylidineisobutylamine were carried out with 1 mol% loading of **IIIA** giving a yield of 48% of the desired product in 5 h. The TOF (first h) and yield of the tested aromatic imines are as follows; N-benzylideneaniline: (136 h^{-1}, 95%);



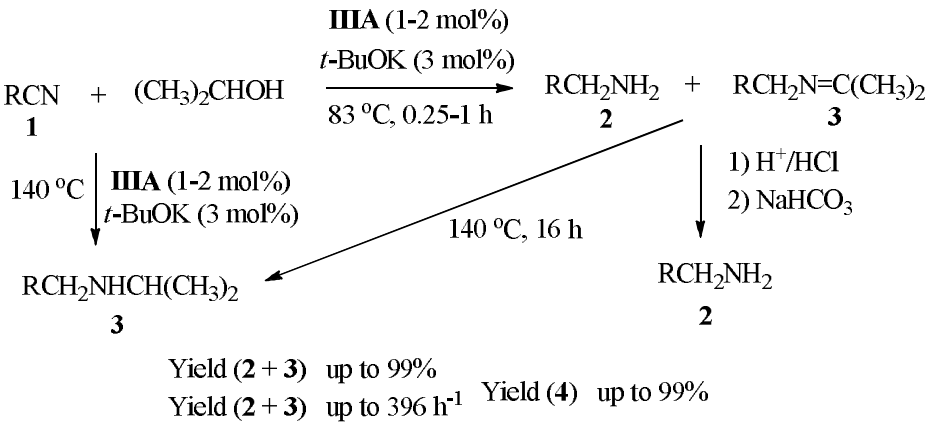
Scheme 15. Transfer hydrogenation of aldimines catalyzed by **IIIA**/*t*-BuOK/2-propanol system.

N-(4-methoxybenzylidene)aniline: (127 h^{-1}, 89%); N-(4-fluorobenzylidene)aniline: (129 h^{-1}, 98%); N-(4-methoxybenzylidene)-4-chloroaniline: (170 h^{-1}, 99%); N-benzylidene-4-chloroaniline: (167 h^{-1}, 95%).

Based on experiments and kinetic studies, a mechanism with **XXVIIA** as the active species is proposed for the transfer hydrogenation of ketones. A β-hydride abstraction to form **XXVIIA** is suggested to be rate limiting. An analogous mechanism is also expected to be operative for the transfer hydrogenations of imines.

Following the studies of transfer hydrogenations of ketones and imines using **IIIA**/*t*-BuOK/2-propanol system, this reaction has been then applied to nitriles (Scheme 11.16), described in Chapter 8. The transfer hydrogenations of aliphatic, aromatic and heteroaromatic nitriles with a temperature controlled selective formation of either primary amines and N-

isopropylideneamines (which can easily be hydrolyzed to primary amines) or reductively alkylation products N-(isopropyl)benzylamine were also realized using complex **IIIA**/*t*-BuOK/2-propanol system. With 1-2.5 mol% of **IIIA** along with 3 mol% of *t*-BuOK carrying out at tempearatures of 83 °C furnished primary amines and isopropylideneamines ($RCH_2N=(CH_3)_2$ in good to excellent yields. This reaction when carried out at 140 °C gave



Scheme 11.16. Selective Transfer hydrogenation as well as reductive alkylation of nitriles to amines and *N*-alkylisopropylamine respectively using **IIIA**/*t*-BuOK/2-propanol system.

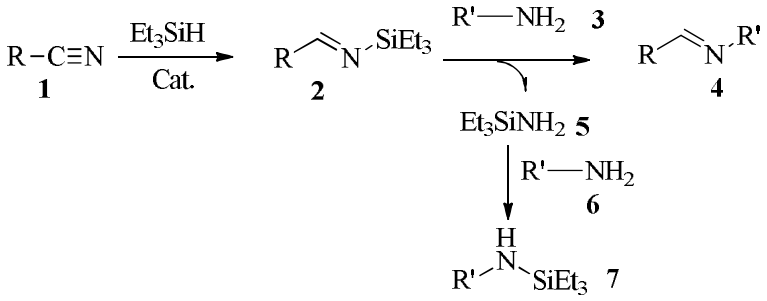
rise to the reductively alkylated products N-(isopropyl)amines ($RCH_2NHCH(CH_3)_2$respectively, in quantitative yields.

The TOFs for the formation of primary amine and N-isopropylideneamines ($RCH_2N=C(CH_3)_2$ together along with their yields in the transfer hydrogenation reactions of the tested nitriles are as follows; Benzonitrile: (384 h^{-1}, 93%); *m*-tolunitrile: (396 h^{-1}, 99%); *p*-tolunitrile: (376 h^{-1}, 94%); *p*-anisonitrile: (252 h^{-1} (first h), 83%); 2-bromobenzonitrile: (392 h^{-1}, 98%); 4-bromobenzonitrile (388 h^{-1}, 97%); 3-trifluoromethylbenzonitrile: (396 h^{-1}, 99%); 3-phenoxybenzonitrile: (396 h^{-1}, 99%); 3,4-difluorobenzonitrile: (192 h^{-1}, 96%); 2-thiophenecarbonitrile: 98 h^{-1} (first h), 90%; cyclohexanecarbonitrile: (120 (first h), 94%); phenylacetonitrile, (182 h^{-1} (first h), 95%).

For the reductively alkylation products **4**, the yield are given as; R = Ph (93%), *p*-anisonitrile (69%), 3-trifluoromethylbenzonitrile (99%), 3-phenoxybenzonitrile (99%).

A mechanism analogous to those proposed for the transfer hydrogenations of ketones and imines is suggested for this transfer hydrogenations of nitriles with **XXVIIA** as the active species.

Efficient hydrosilylations of nitriles using Et_3SiH was also described in Chapter 9, with a mechanism involning **VA** as the active species. TOFs of up to 98 h^{-1} were achieved with almost equimolar ratios of nitriles and Et_3SiH were subjected to hydrosilylation reaction at 80 °C to furnish the corresponding N-silylaldimines up to 98%



Scheme 11.17. Hydrosilylation of nitriles and synthetic utility of the formed silylimines for the production of higher imines/amine protection.

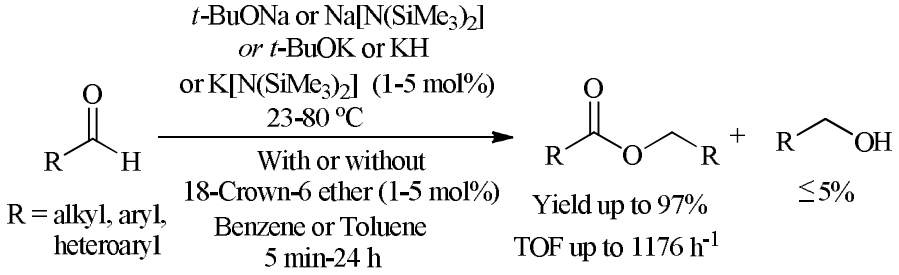
Yield (Scheme 11.17). Aliphatic nitriles were much less efficient for this reaction even at a temperature of 120 °C. For the first time, a synthetic utility of the N-silylaldimines were explored in a one-pot fashion by the addition of amines to the formed N-silylaldimines and that any nucleophilic addition to N-silylaldimines are scarce in literature.

The TOF and yield for the formation of N-silylimines (**2**) are as follows; benzonitrile: (78 h^{-1}, 98%); R = *m*-tolunitrile: (65 h^{-1}, 98%); *p*-tolunitrile: (78 h^{-1}, 98%); 2-bromobenzonitrile: (65 h^{-1}, 98%); 4-bromobenzonitrile: (32 h^{-1}, 42%); 3-trifluoromethylbenzonitrile: (4 h^{-1}, 42%); 3,4-difluorobenzonitrile: (98 h^{-1}, 98%); 3-chloro-4-

fluorobenzonitrile: (66 h^{-1}, 95%); 2-thiophenecarbonitrile: (22 h^{-1}, 88%); phenylacetonitrile: (8 h^{-1}, 33%).

Most of the transformations summarized above using rhenium complexes are either comparable or even much more active in comparison to the corresponding transformations reported using any homogeneous catalytic systems reported in literature.

Finally, simple and efficient method for the Claisen-Tishchenko disproportionation of aldehydes to the corresponding carboxylic esters using alkali metal hydride, *tert*-butoxides and bis(trimethylsilyl)amides has been described (Scheme 11.18). When 18-crown-6 was added ad a co-catalyst to the reactions catalyzed by potassium derivatives, a drastic increase



Scheme 11.18. Claisen Tishchenko reaction of aldehydes catalyzed by sodium or potassium compounds.

in rate of reaction was observed in few cases showing TOFs of up to 1176 h^{-1} completing the reaction even in 5 min with yields of up to 97%. Based on experimental studies, a mechanism involving the metal alkoxide as active species is proposed for these reactions.

List of New Compounds

1. 4,6-Bis(diphenylphosphino)-10,10 diphenylphenoxasilin (Sixantphos-Ph_2) (**B**)
2. [Re(**A**)(CH_3CN)Br_2(NO)], **A** = 4,6-Bis(diphenylphosphino)-10,10 dimethylphenoxasilin (Sixantphos) (**IIA**)
3. [Re(**B**)(CH_3CN)Br_2(NO)], **C** = 4,6-bis(diphenylphosphino)phenoxathiin (Thixantphos) (**IIC**)
4. [Re_2(**A**)$_2$$(Br)_2$(μ-Br)$_2$(NO)].2$CH_3CN$; (**IIIA**)
5. [Re(oC_{PPh}-**A**)(η^2-ethylene)Br(NO)] (**VIIA1**)
6. [Re(oC_{PPh}-**A**)(η^2-ethylene)Br(NO)] **VIIA2**
7. [Re(oC_{PPh}-**B**)(η^2-ethylene)Br(NO)] (**VIIB1**)
8. [Re(oC_{PPh}-**B**)(η^2-ethylene)Br(NO)] (**VIIB1**)
9. [Re(POP)I_2(NO)] (**XIIIA**)
10. [Re(POP)Br_2(NO)] (**XVIIIA**)
11. [Re(**D**)Br_2(CH_3CN)$_2$(NO)], **D** = DBFmonophos (**XIVD**)
12. [Re(**A**)(NH_3)Br_2(NO)] (**XVIA**)
13. [Re(**A**)(PhCH=NH)Br_2(NO)] (**XVIIA**)
14. [Re(**A**)Br_3(NO)][NEt_4] (**XIXA**)
15. [Re(**A**)Cl_3(NO)][NEt_4] (**XXA**)
16. [Re_2(**A**)$_2$$\mu$-$(OH)_3$$(NO)_2$] (**XXVIA**)

Abstract

Homogeneous catalytic processes are often based on precious metals like rhodium, iridium, ruthenium, palladium and platinum. Rhenium being border to precious metals has preserved at least some of the precious metal characters. This thesis explored the ability of novel nitrosyl diphosphine rhenium(I) complexes for a variety of transformations like hydrogenations of alkenes and alkynes to alkanes, aldehydes, ketones and esters to alcohols, imines including direct reductive aminations and nitriles to amines, carbon dioxide and bicarbonates to methanol and formates. Also, transfer hydrogenations of ketones to alcohols, imines and nitriles to amines and hydrosilylations of nitriles to N-silylaldimines as well as Claisen-Tishchenko disproportionation of aldehydes to esters were described. Most of these reactions are comparable and some are even much more active compared to the reported precious metal catalysis. Claisen-Tishchenko reaction of aldehydes to esters using alkali metal compounds was also realized.

Zusammenfassung

Homogene katalytische Prozesse basieren oft auf edlen Metallen wie etwa Rhodium, Iridium, Ruthenium, Palladium oder Platin. Rhenium, welches an der Grenze zu diesen Edelmetallen steht, verfügt zumindest teilweise über den benötigten Edelmetallcharakter. Die vorligende Arbeit untersucht die Eignung neuer Nitrosyl Diphosphin Re(I) Komplexe für eine Vielzahl von Transformationen, zum Beispiel die Hydrierung von Alkinen und Alkenen zu Alkanen sowie von Aldehyden, Ketonen und Estern zu Alkoholen, Nitrilen und Iminen – einschliesslich reduktiver Aminierung – zu Aminen, Kohlenstoffdioxid und Bicarbonaten zu Methanol und Formiaten. Zudem werden die Hydrierung von Ketonen zu Alkoholen, Iminen und Nitrilen zu Aminen und die Hydrosilylierung von Nitrilen zu N-Silylaldiminen sowie die Claisen-Tishchenko Disproportionierung von Aldehyden zu Estern beschrieben. Die meisten der hier beschriebenen Reaktionen sind vergleichbar mit bekannten edelmetallkatalysierten Umsetzungen oder übertreffen diese. Auch die Claisen-Tishchenko Reaktion von Aldehyden zu Estern unter Beteiligung von Alkalimetallverbindungen wurde realisiert.

Acknowledgements

I would like to thank several people who were involved in various ways during the accomplishment of my research work.

First of all, I would like to thank my supervisor Prof. Dr. Heinz Berke for giving me the opportunity to work in his laboratory and introducing me an interesting and challenging field of scientific research. I will remain indebted to him forever for lot of scientific discussions, ideas, guidance towards proper directions, encouragement and support.

Appreciation and thanks is also gratefully expressed to Prof. Dr. Roger Alberto for his kind acceptance to co-referee this dissertation.

I thank Dr. Olivier Blacque for solving lot of crystal structures during my research work.

I thank Dr. Thomas Fox for measuring some NMR samples and discussions regarding them.

I would like to extend my thanks to Heinz Spring and Barbara Spring for measuring all the elemental analyses.

Many thanks to Dr. Koushik Venkatesan for his enormous help and encouragement in various ways throughout my research work.

Thanks to Hanspeter Stadler for helping hand anytime for technical problems regarding glove box or gas room. I would really appreciate his innovative set up in the gas room.

Thanks to Dr. Balz Dudle for scientific discussions and suggestions during the initial part of my research work.

Thanks to Dr. Christian Frech for some scientific discussions.

I would like to express my gratitude to the administrative staff; Beatrice Spichtig, Susanna Sprokkereef, Nathalie Fichter, Dr. Jae Kuoung Pak, Ramona Erni, Manfred Jöhri and Dr. Ferdinand Wild.

I would like to thank my colleagues and friends for making nice working ambiences and extending helping hands in various ways during these years; Dr. Jai Anad Garg, Dr. Subrata Chakraborty, Dr. Samir Barman, Dr. Rajkumar Jana, Dr. Pandiarajan Devaraj, Dr. Yan Li, Dr. Carolina Egler, Dr. Yanfeng Jiang, Dr. Anne Landwehr, Gabriele Grieco, Michael Koch, Franziska Lissel, Pascal Plüss, Miriam Oberholzer, Alexander Szentkuti and Michel Bachmann. Thanks a lot to all of you for making my stay in Zürich memorable.

I thank all the members of Inorganic Chemistry Institute.

I thank the University of Zurich, Swiss National Science Foundation and Lanxess AG (Leverkusen, Germany) for financial support.

Thanks to Prof. Dr. K. K. Balasubramanian and Dr. R Saiganesh and M. Somasundaram for their scientific assistance during my stay in Shasun Research Centre, Chennai.

Thanks to Prof. Dr. Irishi N. N. Namboothiri for his scientific guidance during my stay in Indian Institute of Technology Bombay.

I also thank all my teachers as well as all those inculcate in me several good qualities.

Thanks to my native friends Binil P. Sasidharan and Jayachandran V for their help.

Finally my special thanks to my father N. Kunjanpillai (Late), mother Kamalakshiamma, wife Sujatha Rajesh, daughter Kavyalakshmi R, brothers K. Kuttanpillai, K. Sasi Kumar and K. Santhosh Kumar, sister-in-laws Bindhu K. Pillai, Geetha S. Pillai and Rani S. Pillai, my niece Kavitha K, nephews Kannan K, Nandu S. Pillai, Sabarinath S. Pillai and Sathamanyu S. Pillai.

Curriculum Vitae

Name:	**RAJESH KUNJANPILLAI**
Date of Birth:	15th October 1980
Gender:	Male
Nationality:	Indian
Martial Status:	Married to Sujatha Pullakhandam
Children:	Kavyalakshmi R (Daughter)
Current Position:	PhD Student (01st June 2009 – till date) University of Zürich, Switzerland. Title of the Thesis: Homogeneous Hydrogenations and Related Reductive Reactions Catalyzed by Rhenium Complexes Advisor: Prof. Dr. Heinz Berke

Education

University / Institute	Degree	Year
University of Zürich, Zürich, Switzerland	PhD (Pursuing)	2009-2013
Pondicherry University, Pondicherry, India	Master's Degree in Chemical Sciences	2003-2005
M.G.University College of Teacher Education, Pathanamthitta, India	Bachelor's Degree in Education	2001-2002
St. Stephen's College, Pathanapuram, India	Bachelor's Degree in Chemistry	1998-2001

Professional Experience

Academic		
Institute/Industry	**Designation**	**Duration**
Department of Chemistry, Indian Institute of Technology Bombay, Mumbai	Senior Research Fellow	18th Sept. 2008-08th May 2009
Industry		
Shasun Research Centre, Chennai	Research Associate (R & D Officer)	14th July 2005-30th Aug. 2008

Academic Achievements

- Passed UGC-CSIR-National Eligibility Test for Lectureship, June 2006, conducted jointly by University Grants Commission (UGC) and Council of Scientific and Industrial Research (CSIR), India.

Awards and Honors

- Swiss Academy of Sciences/Swiss Chemical Society (SCNAT/SCS) Chemistry Travel Award 2012.

Research Interest

- Organometallic Chemistry: Structure, reactivity and mechanistic studies, Organometallic homogeneous catalysis including asymmetric versions, Organic transformations using organometallic complexes or catalysts.

- Synthetic Organic Chemistry: Carbon-Carbon and Carbon-Heteroatom (N, O, S, halogen) bond forming reactions, Reactions involving hydride transfer, Organic methodology, Organosilicon chemistry, Stereoselective transformations etc.

Scientific Research Publications

Published

6. Alkali Metal *t*-Butoxides, Hydrides and Bis(trimethylsilyl)amides as Efficient Homogeneous Catalysts for Claisen-Tishchenko Reaction.
Kunjanpillai Rajesh, Heinz Berke, *Adv. Synth. Catal***. 2013**, *355*, 901-906.

5. Homogeneous Hydrogenations of Nitriles catalyzed by Rhenium Complexes.
Kunjanpillai Rajesh, Balz Dudle, Olivier Blacque, Heiz Berke, *Adv. Synth. Catal*. **2011**, *353*, 1479-1484.

4. Rhenium in Homogeneous Catalysis: [ReBrH(NO)(labile ligand)(large-bite-angle diphosphine)] Complexes as Highly Active Catalysts in Olefin Hydrogenations.
Balz. Dudle, **Kunjanpillai Rajesh**, Olivier Blacque, Heinz Berke, *J. Am. Chem. Soc*. **2011**, *133*, 8168-8178.

3. Rhenium Nitrosyl Complexes Bearing Large-Bite-Angle Diphosphines.
Balz Dudle, **Kunjanpillai Rajesh**, Olivier Blacque, Heinz Berke, *Organometallics* **2011**, *30*, 2986-2992.

2. One-pot three component α-aminoalkylation of conjugated nitroalkenes and nitrodienes.
Kunjanpillai Rajesh, Pramod Shanbhag, Manjoji Raghavendra, Pallavi Bhardwaj, Irishi N. N. Namboothiri, *Tetrahedron. Lett*. **2010**, *51*, 846-849.

1. Bromination of Deactivated Aromatics - A Simple and Efficient Method.
K. Rajesh, M. Somasundaram, R. Saiganesh, K. K. Balasubramanian, *J. Org. Chem*, **2007**, *72*, 5867-5869.

Unpublished

7. Highly Efficient Homogeneous Catalysis of Direct Reductive Amination of Aldehydes and Hydrogenation of Imines Applying Rhenium Complexes.
Kunjanpillai Rajesh, Olivier Blacque and Heinz Berke.

8. Homogeneous Hydrogenation/Hydrosilylation of Carbon Dioxide to Methanol Catalyzed by Rhenium Complexes.
Kunjanpillai Rajesh, Olivier Blacque, Thomas Fox and Heinz Berke.

9. Homogeneous Hydrogenations of Aldehydes, Ketones, Esters and Bicarbonates to Alcohols, as well as Carbon Dioxide and Bicarbonates to Formates Catalyzed by Rhenium Complexes. **Kunjanpillai Rajesh** and Heinz Berke.

10. Homogeneous Claisen-Tishchenko Reactions of Aldehydes and Transfer Hydrogenation Reactions of Ketones and Imines Catalyzed by Rhenium Complexes. **Kunjanpillai Rajesh** and Heinz Berke.

11. Homogeneous Thermocontrolled Chemoselective Transfer Hydrogenations of Nitriles Catalyzed by Rhenium Complexes. **Kunjanpillai Rajesh** and Heinz Berke.

12. Homogeneous Hydrosilylations of Nitriles Catalyzed by Rhenium Complexes. **Kunjanpillai Rajesh** and Heinz Berke.

Conferences and Seminars

- Kunjanpillai Rajesh, Balz Dudle, Olivier Blacque, Thomas Fox, Heinz Berke, Rhenium-Catalyzed Homogeneous Hydrogenations; XXV International Conference on Organometallic Chemistry, Sep. 2-7, **2012** – Lisbon, Portugal. (Oral Flash & Poster).

- Balz Dudle, Kunjanpillai Rajesh, Olivier Blacque, Heinz Berke, Rhenium-Catalyzed Homogeneous Hydrogenations, Swiss Chemical Society Fall Meeting **2011**, 09.09.2011, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne. (Poster).

- Developing Rhenium Catalysts for Homogeneous Hydrogenation Reactions, Swiss-German Project; Unconventional Approaches to the Reactivity of Dihydrogen, 11.02.**2011**, Swiss Federal Institute of Technology (ETH) Zurich, Zurich, Switzerland. (Oral).

Permanent Address: Pullam Madathil
Kaithaparampu Post
Enathu
Pathanamthitta District
Kerala State - 691526
India